OULUN YLIOPISTO

FACULTY OF TECHNOLOGY

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DEGREE PROGRAMME OF GEOSCIENCES

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Oulun yliopisto, Teknillinen tiedekunta

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Tiivistelmä

Opinnäytetyö tehtiin yhteistyössä Keliber Oy:n ja Oulun yliopiston kanssa. Työssä tutkittiin Keliber Oy:n Keski-Pohjanmaalla, Kaustisen ja Kokkolan kuntien alueella sijaitsevien litiumrikkaiden spodumeenipegmatiittien malmin ja sivukiven erottelua ja mallintamista. Työn tavoitteena oli luoda spodumeenipegmatiittimalmeille soveltuva indeksi, jonka avulla voidaan kuvata tarkasti malmin ja sivukiven määrää malmiesiintymässä alueellisesti. Indeksillä voidaan arvioida malmin esirikastamisen tarvetta ja sen tuomia hyötyjä. Se voidaan ottaa avuksi kaivos- ja louhintasuunnitteluun sekä malmiesiintymän mallintamiseen. Kaustisen alueen spodumeenipegmatiittien ja sivukivien väriero mahdollistaa sensoripohjaisten menetelmien käyttämisen esirikastusvaiheessa malmin ja sivukiven erottelussa. Lisäksi työssä tutkittiin mahdollisuutta erottaa litiumpitoinen spodumeenipegmatiitti litiumköyhästä pegmatiitista optisia menetelmiä käyttäen.

Työssä määritettiin Rapasaaren spodumeenipegmatiittiesiintymän yhdelle malmijuonelle indeksi, joka kuvaa malmin ja sivukiven lajittelun tarvetta sekä sen tuomaa hyötyä. Indeksi esitettiin prosenttiosuuksina kairasydänmittaväleistä kairasydänten uudelleen raportoinnissa. Kairasydänraportoinnista saadusta tiedosta tehtiin blokkimallit, jossa kokeiltiin indeksin toimivuutta. Laboratoriomittakaavainen tutkimus sensoripohjaisen erottelun toimivuudesta malmin ja sivukiven erottelussa tehtiin Syväjärven ja Läntän spodumeenipegmatiitti- ja sivukivinäytteille. Tutkimuksessa pyrittiin erottamaan myös spodumeenipegmatiitti litiumköyhästä pegmatiitista. Näytteet sisälsivät eri pitoisuuden omaavia spodumeenipegmatiitti- ja kvartsi-albiitti-muskoviittipegmatiittikappaleita, kalimaasälpäkappaleita sekä sivukivikappaleita. Käytetyt sensorit olivat COLOR, NIR, XRT ja LASER. Hyperspektritutkimus tehtiin valituille Rapasaaren esiintymän kairasydämille. Hyperspektritutkimuksella pyrittiin selvittämään spodumeenipegmatiittien mineralogiaa sekä piirteitä, joilla se voidaan optisesti erottaa litiumköyhästä pegmatiitista.

Indeksiin perustuen Rapasaaren spodumeenipegmatiittijuonen laskettiin sisältävän 15 prosenttia tummaa sivukiveä ja 14 prosenttia litiumköyhää pegmatiittia. Malmilävistyksien keskiarvoiseksi litiumoksidipitoisuudeksi saatiin 1,16 %. Blokkimallinnuksessa saatu tumman sivukiven määrä oli 12,2 %. Litiumköyhän pegmatiitin määrä oli 13,9 %. Kehitetty indeksi toimii myös muiden malmien yhteydessä. Indeksiä voidaan soveltaa, kun malmi ja sivukivi ovat erotettavissa kairasydänraportointia tehdessä. Sensoripohjaisen lajittelun todettiin erottelevan vaalea malmi ja tumma sivukivi 100 prosentin todennäköisyydellä kaikkia sensoreita käyttäen. LASER oli ainoa sensori, joka havaitsi eroja spodumeenipegmatiitin ja litiumköyhän pegmatiitin välillä. LASER-sensori hyväksyi 88% malmiksi luokitelluista kappaleista tuotteeksi, mutta hylkäsi 12 % malmikappaleista jätteeksi.

Muita tietoja

ABSTRACT FOR THESIS

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Abstract

This Master of Science project is supervised by Keliber Oy in co-operating with University of Oulu. Lithium rich spodumene pegmatite deposits of Keliber Oy locate in Central Ostrobothnia, Finland. Studied deposits locate in the municipalities of Kaustinen and Kokkola. The study was focusing on mechanical separation of ore and waste rock and spatial modelling of sorting properties of the ore. The aim of the study was a development of index, that is suitable for spodumene pegmatite ores. The index is a spatial estimation of waste rock dilution within the deposit and it is defined during drill core logging. The index is describing the need and benefits for preconcentration of ore and can be used in mine planning and resource modelling. In Kaustinen region, high contrast difference between light coloured spodumene pegmatite ore and dark coloured country rocks is making optical separation methods possible to use in preconcentration. Another aim of the study was to found methods to separate spodumene pegmatite and barren pegmatite, similar in colours, by sensor-based sorting.

The index was defined for one spodumene pegmatite dike of the Rapasaari deposit. The index was represented as percentages of ore from drill core interval and was defined during drill core relogging. There was made block models for black country rocks and barren pegmatite from data of relogged drill cores. Block models included the sorting index. Bench-scale sorting test was done for separation of spodumene pegmatite and barren pegmatite. Also, separation potential of sensor systems for ore and country rock was verified. The used samples were from the Syväjärvi and the Länttä deposits and they included spodumene pegmatite pieces with different grades, quartz-albite-muscovite pegmatite pieces, potassium feldspar pieces, and country rock pieces. Hyperspectral imaging test was done to the selected drill cores of the Rapasaari deposit. Hyperspectral study was done for study of mineralogy and features of spodumene pegmatites.

According to the sorting index, the determined amount of waste rock within the ore dike was 15 weight percent and amount of barren pegmatite was 14 weight percent. Average lithium oxide grade of studied ore intercepts was 1.16 %. In block modelling, the amount of black waste rock was 12.2 wt.% and the amount of barren pegmatite was 13.9 wt.%. The index is suitable for all ores, where ore and waste rock can be positively identified during drill core logging and sorting. In bench-scale sorting test, it was found that all sensor systems are capable to separate pegmatites and country rock. The LASER sensor system was the only one, that could positively identify differences between spodumene pegmatite and barren pegmatite. However, the LASER sensor accepted 88 % of ore samples to the product (i.e. preconcentrate) but rejected 12 % of the ore samples as reject (i.e. waste).

Additional Information

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In Oulu, 14.10.2018 Henri Äijälä

TABLE OF CONTENT

ABBREVIATIONS

CCD	a colour line scan camera
HS	hyper spectral
LCT	lithium-caesium-tantalum
LWIR	long-wave infrared
MLA	mineral liberation analyser
NIR	near infrared
RGB	a high resolution natural colour camera
ROM	run-of-mine
SBS	sensor-based sorting
SWIR	short-wave infrared
T	temperature
VNIR	visible to near infrared
XRT	X-ray transmission

B	boron
Be	beryllium
Cs	caesium
Cu	copper
F	fluorine
Fe	iron
Li	lithium
Li_2O	lithium oxide
K	potassium
Mn	manganese
P	phosphorous
Rb	rubidium
Sn	tin
Ta	tantalum
U-Pb	uranium-lead

1 INTRODUCTION

Crushing and milling plays major role in the consumption of electricity and water in mining industry. It is widely recognized (Baum 2013; Lessard et al. 2014; Lessard et al. 2016) that rising costs of the power and water and fallen ore grades create economic challenges to many mining companies. One way to lower the operating costs is in preconcentration of ore. By preconcentrating the ore, it is possible reject waste rock and gangue minerals in early stages of the process reducing operational costs per ton of product. That can have a major economic impact making mining projects more profitable (Lessard et al. 2014).

A preconcentration method studied here is a sensor-based ore sorting (SBS) that is suitable for especially coarse ores. SBS is a cost-effective way to separate the valuable rocks or minerals from waste rocks in a run-of-mine (ROM) stream after primary crushing (Lessard et al 2014). That has direct reduction on waste rock dilution in the concentration process. SBS machines can be used either at the mine site or in the concentration plant before the comminution circuit. Sorting at the mine site reduces transportation costs of the ore and lowers the amount of waste rock in the plant feed that has impact on milling and processing costs. SBS methods are possible to use where the ore and country rock have sharp contacts and differ physically or chemically from each other.

In Kaustinen region several spodumene pegmatite deposits have been discovered. The area characterized by spodumene pegmatite deposits, is called Kaustinen Lithium Province. Spodumene pegmatites in Kaustinen Li Province have a high colour contrast between "white" host rock and "black" waste rock. That enables the use of optical sensor-based sorting for separating the ore and the waste rock. Spodumene pegmatites of Kaustinen Li province are the rare element (RE) granitic pegmatites. More precisely classified, after Černý and Ercit's (2005) classification of granitic pegmatites, they belong to the LCT pegmatite family. The LCT pegmatites are enriched in Li, Cs and Ta with Rb, Be, Sn, B, P and F in some cases. The LCT family is subdivided to several different groups of pegmatites and spodumene pegmatites of Kaustinen Li province belong to the albite-spodumene group.

The main objective of this study is the development of sorting index that is suitable for spodumene pegmatite ores. The sorting index can be used in mineral resource modelling to estimate the waste rock dilution before and after sensor-based sorting. The sorting index is defined based on data collected during geological drill core logging. The log information can be used in mineral resource modelling, ore reserve estimation and mine planning; thus, in block modelling. Another objective is to study methods to separate spodumene pegmatite and barren pegmatite with SBS. Separation of country rock and barren pegmatite in the run-of-mine can give major savings in processing costs.

Experimental part of the study covers the development of sorting index with geological relogging of chosen drill cores. Relogging was carried out for selected ore including variation in grade and texture, and in waste rock types. Relogging and sorting index calculations were done for 28 drill cores of the Rapasaari deposit. All the drill cores are related to the same spodumene pegmatite dike. Block models were done for barren pegmatite and black waste rock based on relogged drill core data. Hyperspectral imaging trial was executed for selected drill core intervals to study the mineralogy of spodumene pegmatites, but also to evaluate whether hyperspectral sensors could provide more effective identification of the ore and barren waste rock. Bench-scale sorting test was done for optimization of sorting process. Samples for bench-scale sorting tests were chosen from the test pits at Syväjärvi and the Länttä deposits. Deposits mentioned above are the most developed deposits in the Kaustinen Li province and widely prospected with drilling and sampling. Valid data from each deposit are providing a good basis for this thesis project.

This Master of Science study is supervised by Keliber Oy in co-operating with University of Oulu. The bench-scale sorting test was done with co-operating with Outotec Oy and TOMRA Sorting GmbH. The test was proceeded in TOMRA Sorting Test Center at Hamburg-Wedel, Germany. The hyperspectral imaging trial was done by professionals of TerraCore with sisuROCK machine. The MSc. study is a part of the transnational FAME-project (http://www.fame-project.info/) and funded by the FAME and Keliber Oy.

2 GEOLOGICAL SETTING OF KAUSTINEN LITHIUM PROVINCE

The Kaustinen lithium province includes several spodumene pegmatite deposits and occurrences (Figure 1). Most of the deposits locate in the areas of municipalities Kaustinen and Kokkola in the Western Finland. Supracrustal rocks of the Kaustinen Li province are part of the Pohjanmaa schist belt. The Pohjanmaa schist belt, which is part of the Paleoproterozoic Svecofennian arc complex, locates between the Central Finland granitoid complex in the east and Vaasa migmatite complex in the west. The area of the Kaustinen Li province is circa 500 km^2, but according to Kontoniemi (2013), anomalies in regional till geochemistry could be indicating even wider area.

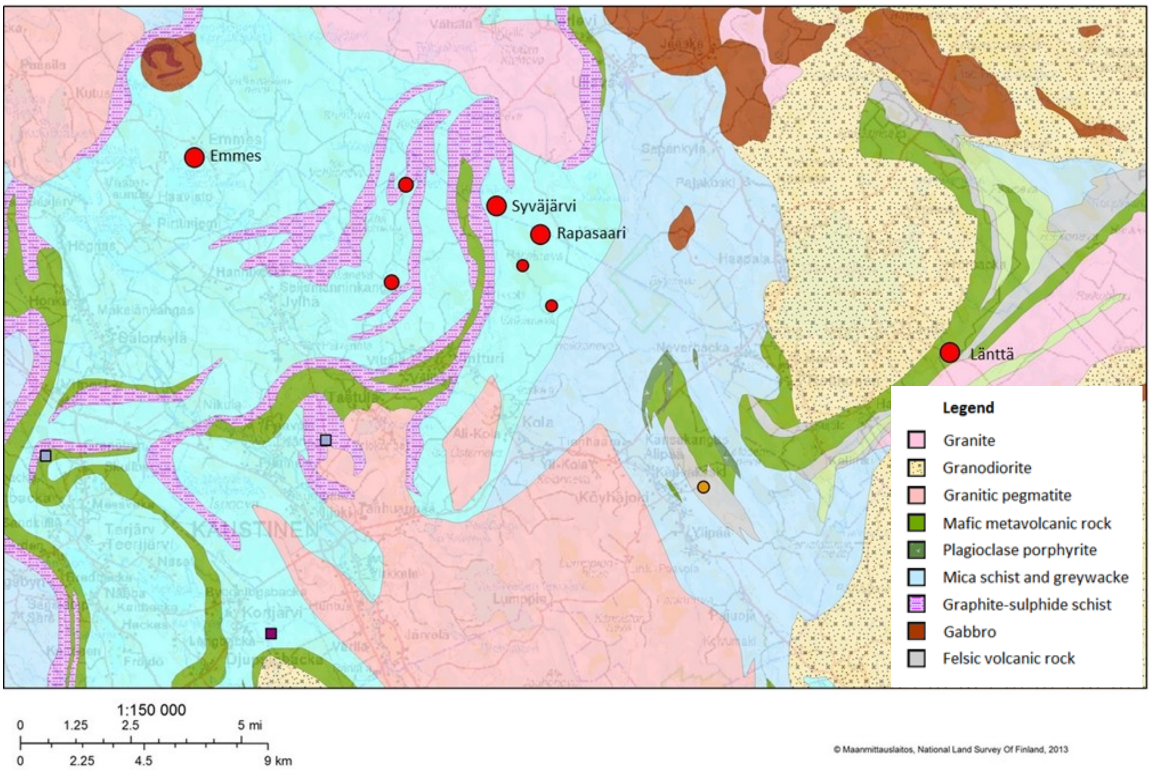


Figure 1. Locations of spodumene pegmatite deposits (red circles) in Kaustinen-Kokkola-Kruunupyy area. (Modified from Mineral deposits and exploration -active map by Geological Survey of Finland)

The Pohjanmaa schist belt is divided into two fields: Evijärvi field and Ylivieska field (Kähkönen 2005). In the Evijärvi field, the dominating rocks are turbiditic greywackes and mudrocks, but there are also units of mafic lavas with mid-ocean ridge basalt (MORB) to within-plates lava (WPL) affinities with associated black shales, carbonate and calc-silicate rocks, and cherts. The metamorphic grade in the Evijärvi field increased from medium temperature amphibolite facies in the northeast to lower temperature granulite facies in the southwest. That produced metamorphosed schists, gneisses and locally migmatites (Kähkönen 2005).

The rocks of the Ylivieska field are mostly arc-type volcanic rocks with relating clastic sedimentary rocks, which occur as scattered complexes. The metamorphic grade in the Ylivieska field varies from lower-T amphibolite facies to medium-T amphibolite facies. Primary structures of the rocks are well preserved and still abundant in the rocks. Metavolcanic rocks in the Ylivieska field are pyroclastic to volcanoclastic origin with rocks for lava origin also. Those includes rocks from basalts to K-rhyolite with calc-alkaline, mature island-arc affinity. The rocks with sedimentary origin are slightly metamorphosed sandstones, conglomerates, and silty mudrocks with volcanic provenance (Kähkönen 2005).

The spodumene pegmatites are intruded into northern continuation of the Evijärvi field (Ahtola et al. 2015) metavolcanic and metasedimentary rocks. Wall rocks comprise metagreywackes and mica schists with some black schists and metavolcanic rocks (Alviola et al. 2001). According to Alviola et al. (2001), U-Pb columbite age of the spodumene pegmatites is 1.79 Ga. Ages of the Svecofennian supracrustal rocks, which are crosscutted by spodumene pegmatites, are 1.95-1.88 Ga.

Martikainen (2012) suggested that the source of the albite-spodumene pegmatites of the Kaustinen Li province could be pegmatite granites which occur in Kaustinen area. Pegmatite granite of Kaustinen is plausible source for spodumene pegmatites as it is the most developed granitoid in the region by its composition and the fractional crystallization model supports the hypothesis too (Martikainen 2012). However, the lack of specific age determinations from pegmatite granites of Kaustinen makes the definition of source granitoid uncertain.

2.1 The Syväjärvi deposit

The Syväjärvi lithium deposit is composed of several spodumene pegmatite dikes. According to the current studies, the pegmatites are long lensoids that are trending north-northwest. The plunge of pegmatites is 15-20 degrees to north-northwest (Keliber 2016).

Mineralogy of the spodumene pegmatites in Syväjärvi area is typical for the albite-spodumene type LCT pegmatite. The main minerals are spodumene, quartz, albite, K-feldspar and muscovite. The spodumene grain distribution is varying in the dike. The spodumene content is increasing from wall rock contact towards the core of the dike. In some cases, near the contact zone between the wall rock and spodumene pegmatite, spodumene is altered to muscovite. Grain size of spodumene varies from very fine grained to grains which are nearly 50 cm in length and 10 cm in width. Accessory minerals of the spodumene pegmatites are apatite, Mn- and Fe-tantalite, tourmaline, garnet, arsenopyrite and sphalerite. Barren muscovite pegmatites, without spodumene, do occur in the Syväjärvi area also (Ahtola et al. 2010).

Wall rocks of the Syväjärvi deposit are mainly mica schist and metagreywacke and intermediate metavolcanic rocks, mainly plagioclase porphyrite, metatuffs and metatuffites. Spodumene pegmatites are intruded into mica schist and plagioclase porphyrite and are cutting both rock units (Ahtola et al. 2010).

2.2 The Länttä deposit

The Länttä deposit includes two thicker boudinaged dikes of spodumene pegmatite with parallel thinner veins. The boudinage structure is common both in the main dikes and the small veins. The thickness of the dikes is up to 10 metres and they are steep by dipping 70° to southeast with striking from northeast to southwest (Keliber 2016). The veins are intruded into metavolcanics unlike other deposits and their geochemical features differ from other deposits by certain elements (Martikainen 2012).

The wall rocks of the pegmatite dikes are volcanic intermediate rocks with layers of greywacke schist and plagioclase porphyrite. As we see in the Figure 1, the belt is bordered by granites and granodiorites in southeast and northwest. The dikes have also internal wall rock inclusions or layers. In some parts of the deposit, the dikes are split to a swarm of the thinner veins (Keliber 2016).

Also, in the Länttä deposit, mineralogy of the pegmatites is typical for albite-spodumene group pegmatites. The main minerals are albite, quartz, K-feldspar, spodumene, and muscovite. The main accessories are apatite, garnet, beryl, tourmaline, and columbite-tantalite. The spodumene crystals are coarse-grained, with length from 3 to 10 cm, but the maximum length can be 30 cm. Tourmaline has crystallized at the contact of pegmatite and the wall rock forming narrow tourmaline seam. K-feldspar occurs often as large crystals surrounded by albite-quartz-spodumene combination. The Länttä deposit differs from the other spodumene pegmatites by being richer in tourmaline and beryl (Keliber 2016).

2.3 The Rapasaari deposit

The Rapasaari deposit includes several spodumene pegmatite dikes with varying dips and strikes. The thickness of the dikes varies from 1 metre up to 20 metres (Sandberg 2014). The spodumene pegmatite dikes have intruded into wall rocks mainly parallel towards the primary bedding forming several small and large units (Keliber 2016).

The main minerals of spodumene pegmatites of the Rapasaari deposit are albite, quartz, K-feldspar, spodumene and muscovite. Grain size of spodumene is usually 3 to 10 cm in length and less than 1 cm in width. In some pegmatite dikes, spodumene is altered to muscovite nearby the wall rock contact. Muscovite pegmatites are occurring also as their own veins (Sandberg 2014).

Wall rocks of the deposit are mainly mica schists and metagreywacke. The metasedimentary rocks contain andalusite and staurolite porphyroblasts in certain places. Quartz-tremolite skarns with garnet are occurring also. The main accessory mineral is apatite, but there are also several other accessory minerals. Tourmaline is occurring in pegmatites and sometimes in the contacts between pegmatites and the wall rock forming a tourmaline seam in the contact. Other accessories are fluorite, chlorite, zinnwaldite, grossular garnet, andalusite, calcite, beryl, Nb-Ta oxide, pyrrhotite, pyrite, arsenopyrite and Mn-Fe phosphate (Kuusela et al. 2011).

In some parts of the Rapasaari deposit, the spodumene pegmatite dikes are partly weathered and broken up to the depth of 20-30 metres. That kind of extensive surface weathering has not been found in the other pegmatite deposits in the studied area (Keliber 2016).

3 LITHIUM ORES AND THEIR PROCESSING

3.1 Global production and occurrence of lithium

Lithium demand has substantially increased in the last ten years. Increasing number of portable devices, electric tools and electric vehicles which use rechargeable lithium batteries have significant influence to demand of lithium. There are also other uses for lithium, for example in ceramics, glass industry and lubricating greases, but usage in batteries takes more and more larger share of the consumption in every year. Total mine production in the world in 2015 was 32,500 metric tons compared to 31,700 metric tons in 2014 (Jaskula 2015 and Jaskula 2016). Total lithium production with producing countries in 2015 is shown in Figure 2.

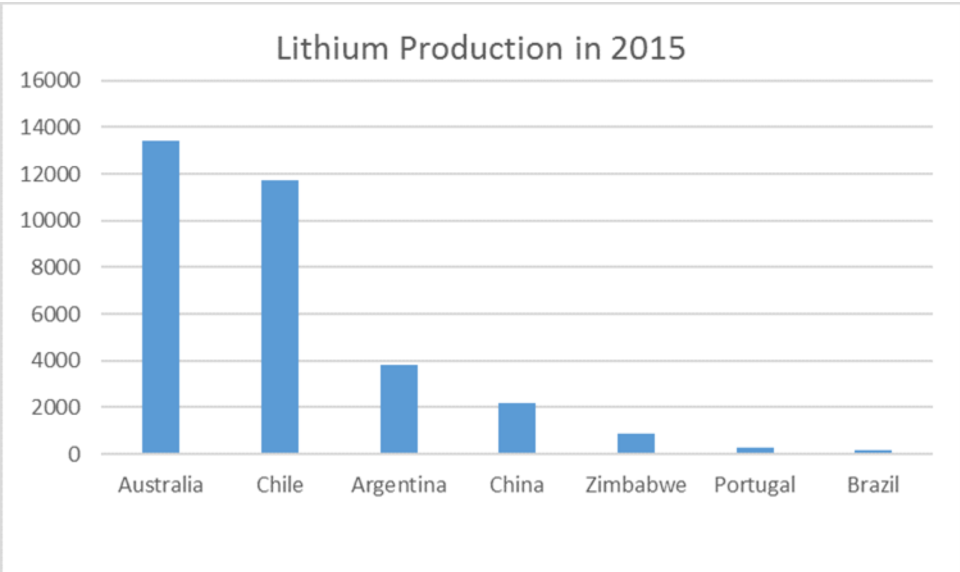


Figure 2. Lithium production in metric tonnes and producing countries in 2015 (Jaskula 2016).

Lithium is the lightest metal on the Earth. It has a high reactivity and because of that lithium occurs in the nature only in form of compounds. Lithium is a lithophile element, so it is concentrated in the Earth's crust. Average abundance of lithium in the crust is 17 ppm, but it varies approximately from 30 ppm in igneous rocks to 60 ppm in sedimentary rocks (Evans 2014).

Commercially potential lithium enrichments are found in pegmatites, continental brines, oilfield brines and geothermal brines. Minerals, besides the ones found in pegmatite, having mining potential, are the clay mineral hectorite and the recently discovered mineral, jadarite. Sources, which are currently used for lithium production, are pegmatites and continental brines. Active lithium mines and advanced-stage lithium projects aiming to produce lithium from pegmatites are in Australia, China, Finland and Canada. Continental brines are used for lithium production in South America, China and USA (Evans 2014). Estimated world total resources of lithium after Evans (2014) are 40.07 million tonnes of which 9.93 Mt is in pegmatites, 25.16 Mt in continental brines and 4.98 Mt in other deposit types. In the late 1990s subsurface brines were dominant source of lithium production because of lower production costs compared to hard-rock ores. Mineral-sourced lithium regained market share in the past several years and was estimated to be one half of the world's lithium supply in 2015 (Jaskula 2016).

Pegmatites containing lithium are quite rare and often contain tin and tantalum. The most common lithium-containing minerals in pegmatites are spodumene ($LiAlSi_2O_6$), petalite ($LiAlSi_4O_{10}$) and a lithium-containing mica, lepidolite [$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$]. Spodumene is the most common mineral and therefore the most important lithium source in pegmatites. Petalite and lepidolite are less common. Other lithium minerals in pegmatites have not a significant economic influence on lithium market (Evans 2014).

3.2 Sensor-based ore sorting

The term sensor-based ore sorting includes all applications where particles are singularly detected by sensor technique and then rejected by an amplified mechanical, hydraulic, or pneumatic process (Wotruba and Harbeck 2012). Ore sorting process is proceeded commonly after primary or secondary crushing, when the sufficient liberation stage of particles is achieved. Preconcentrating by SBS is seen as a method which can improve sustainability of mineral processing operations. With SBS, it is possible to reduce specific materials handling requirements, lowering energy and water consumption in grinding and concentration process, and getting more environmentally sound tailings disposal (Cutmore and Ebehardt 2002; Lessard et al. 2014). The main purpose of the sensor-based sorting is reducing costs of specific investments and processing while an environmental footprint of an operation is reducing (Wills and Finch 2016).

SBS applications can be implemented in mineral processing stages in various tasks. One application is in the preconcentration stages for removing the liberated ore from the waste rock in the ROM feed. The pre-concentrate from this stage is blended with the fine ROM and fed it to the mill and concentration process. The aim of this sorter setting is to get the highest ore recovery percent that is possible, but the grade of the pre-concentrate is of secondary importance (Wotruba and Harbeck 2012).

With SBS, it is also possible to upgrade sub-economic mineral resources to ore reserves by lowering the overall mining losses. The mining losses decrease when "diluted" batches of the ROM ore can be processed. Then it is possible to lower cut-off grade and sub-economic resources can be upgraded to reserves. Other objectives of SBS can be preparation of final products and cleaning, e.g. in diamond concentration, and scavenging and the processing of the old waste-dumps (Wotruba and Harbeck 2012).

3.2.1 Subprocesses of sensor-based sorting

Sensor-based ore sorting is comprised of several subprocesses which have effects on the whole separation task. Subprocesses of SBS after Wotruba and Harbeck (2012) are listed and described briefly below.

Material preparation. The correct material preparation is depending on material that is sorted and processed further after sorting. In separation of particles the prepared material must fulfil the requirements of the separation process. The material must be screened to a range with maximum and minimum size ratio of less than 3:1. Large size range can influence negatively the degree of particle isolation, as smaller particles might get covered by larger ones causing a situation that smaller particles cannot be identified anymore. If sensor applications, which rely in the surface properties of the particles, is used, then the material must be washed, scrubbed or dedusted before sensing process, and dried in some cases.

Material presentation methods. Presenting the single particles to the sensor arrangement is the goal of the isolation process. Therefore, the particles are accelerated and spread out on a larger working width than in the previous conveying mode. That leads particles to separate each other in a conveyor belt. The focus of the particle presentation is getting a single-particle layer, with the densest surface cover that is possible and without particles touching each other.

Measurement of material properties. The identification of material's properties is achieved by the right sensor arrangement. A single sensor is suitable in many cases.

Sensor type is depending on material: for example, a line-scan camera or photodiode array is enough for scanning by colour or brightness. Different sensor types are described in the next chapter. Paramount for successful sorting is the geometrical arrangement of the light source, material and sensors.

Digital image processing. At first, the sensor is providing an endless image data of the material presented by a feeding belt. Then the data stream is evaluated online with digital image capabilities of the sorting electronics. Modern systems are capable for morphological filter operations on high-resolution images and particle-based evaluations in milliseconds. That enables the particle isolation from background by a set of parameters describing particle properties. The sorting decision, particle acceptation or rejection, is derived from these parameters. The information of particles' size and position is used to control ejection mechanism, e.g. position, number, and duration of a solenoid valve activation. That information must be tracked until the correct particle passes the ejection system.

Mechanical separation. The exact rejection of the identified single particles is the main goal of the mechanical separation process. Actuation speed, force and resolution are the key parameters of this process. The choice of these parameters must be done according to the material properties, operating conditions, and especially the contamination of the detection area. Air valves, water jets, and mechanical flaps are the three main methods in use of mechanical separation. Because of having the highest actuation speed and accuracy air valves are almost exclusively used in mechanical separation.

3.2.2 Sensor technologies and applications

SBS utilizes the sensing of electromagnetic radiation from a certain part of a spectrum. Applicable sensors are used to record transmission, reflectance, or fluorescence of the material that is excited with radiation at a certain spectral range (Wotruba and Harbeck 2012). The most typical sensors used in sensor-based sorting are radiometric, X-ray transmission, X-ray fluorescence, colour, photometric, near infrared spectrometry, and infrared camera (Table 1).

Table 1. Sensor types, sorting properties of material and sensor applications (Modified after Wotruba and Harbeck 2012).

Sensor type/technology	Material property	Sorter application
Radiometric	Natural gamma radiation	Radioactive ores
X-ray Transmission (XRT)	Atomic density	Base and heavy metal ores, precious metal ores, industrial minerals, coal, diamonds, scrap metals
X-ray Fluorescence (XRF)	Visible fluorescence under X-rays	Diamonds
Colour (CCD Colour Camera)	Reflection, absorption, transmission	Base metal ores, precious metal ores, diamonds, indrustrial minerals, glass
Photometric (PM)	Monochromatic reflection, absorption	Indrustrial minerals, precious stones, diamonds
Near Infrared Spectrometry (NIR)	Reflection, absorption	Base metal ores, industrial minerals, plastic, paper, cardboard
Infrared Camera (IR)	Heat conductivity, heat dissipation	Base metal sulphide ores, precious metal ores, industrial minerals, graphite, coal

There are several approaches for scanning methods in SBS. All of them are aiming at receiving the electromagnetic radiation reflected by or transmitted through the material that is covering the active width of the sorter. Overall, the scanning method, i.e. used sensors and sensor arrangement, depend on properties of the sorted material.

3.3 Applications of SBS in the mining industry

There are only limited number of proven and publicly documented applications of SBS within the mining industry. However, technological developments on available sensors and increasing throughput of automated sorting machines have raised the interest develop sorting solutions for the mining industry. Some of the studies are introduced below.

Dalm et al. (2014) investigated application of NIR spectroscopy in SBS of a porphyry copper ore. The target of the study was to test a NIR sensor in discrimination of Cu grades in ore samples. They found a relation between the hydrothermal alteration mineralogy and Cu grade, but they could not determine Cu-bearing minerals with NIR spectroscopy. However, they found that such an application could have potential for economic benefits within porphyry Cu deposits.

Lessard et al. (2014) used a dual energy X-ray transmission array for the sorting of molybdenum ore. They achieved molybdenum recoveries from 65.6 % to 93.4 % and the waste rejection of 40.2-93.7 %. Based on grinding models they calculated potential energy savings of more than 60 % due to waste rejection.

Ridaskoski (2014) studied in his MSc. thesis optical SBS application for two orogenic gold deposits. He found that the sensor-based sorting is suitable for marginal- and low-grade orogenic gold deposits, which have a sharp and detectable contact between ore and waste rock. SBS removed waste rock 41-61 wt.% in a lower grade deposit and increased gold grade from 5.1 ppm to 8.1-12.0 ppm with gold recoveries of 96 % to 93 %. A high-grade deposit showed 15-32 wt.% waste rock removal with gold recoveries 97 % to 92 %. The gold grade increased from 7.2 ppm to 8.2-9.6 ppm. He also found that the quality of the products got better when harmful minerals were rejected.

3.3.1 Preconcentration of lithium ores

In global scale, hard rock lithium ores are mainly concentrated by flotation or dense media separation. Separation by hand sorting has been historically used with spodumene ores (Schwartz 1925; Munson and Clarke 1955). Hand picking has been used also with coarse grained petalite ores in Africa and China. Two major producers of spodumene concentrate, Bernic Lake (Canada) and Greenbushes (Australia), do not use sorting. In Bernic Lake, spodumene is preconcentrated by dense media separation and flotation. Flotation is used in Greenbushes (Bulatovic 2015).

Keliber Oy has done a pilot scale bulk test for sorting of spodumene using Outotec / TOMRA's technology (Outotec 2016). The primary aim of the test was the removal of black waste rock from the plant feed. Secondary task was to remove pure feldspar from the plant feed. Used sensors were a colour line scan CCD camera and a NIR scanner. They found that the sorting system's ability to separate black waste rock out from the plant feed was 100 %. The amount of black waste rock did not affect to the sorting result. The separation of feldspar was also proved to be possible with the test (Outotec 2016).

3.4 Other methods to reject waste rock

There are several other methods which are used in separation of a waste rock and an ore. These include for example magnetic separation, dense media separation and gravity concentration. It is also possible to reject waste rock with selective mining, or selective loading during mining operations. Methods which can or may be applied with spodumene pegmatite dikes of Kaustinen region are selective mining or loading and magnetic separation within the Länttä deposit.

3.4.1 Selective mining and loading

Selective mining can be used when the ore and the waste rock have a sharp contact and the mining plans are detailed. Precise knowledge of the ore body and modelled mine blocks are needed in implementation of selective mining, with an expertise and a co-operation of a mine geologist and mining engineer.

For example, selective mining can be used in vein-hosted deposits, which have a detectable contact to waste rock. This is done by drilling along the vein contacts and separate the ore and the waste rock by careful blasting. After blasting, it is possible to get bigger waste rock blocks separated out of the ore by selective loading already in primary stope loading. (Keliber 2016)

According to Bowman and Bearman (2013) the traditional path of selective metal extraction has two basic stages of waste rejection. The first stage is the outlining of ore and waste for development and execution of the mine plan. The second stage is the liberation by grinding of all material that is deemed “not waste” to the necessary size for effective extractive metallurgy. In this kind of process, there are three overall waste streams generated: the ROM waste, milling scats, and tailings. Especially the milling scats are not always fully rejected but can be re-crushed and returned into the process (Bowman and Bearman 2013).

3.4.2 Magnetic separation (cobbing)

Magnetic separation can be used for separation of magnetic ore or for removal of magnetic waste rock from the ROM feed. With the method, it is also possible to separate magnetic and non-magnetic valuable minerals from the mixture. Magnetic separators process continuously material from a constant stream of a particles which is passing through a magnetic field (Wills and Finch 2016).

Cobbing is magnetic separation of larger magnetic rock particles out of the ROM feed. The method is used, for example, with coarse magnetic ores (Parker 1977). Mafic metavolcanic wall rock of the Länttä deposit contains a small amount of magnetic mineral, which may enable cobbing separation.

3.5 Hyperspectral imaging

Hyperspectral imaging can offer specific information that cannot be detected by human eye from geological samples, e.g. drill cores. Hyperspectral imaging enables the digital imaging of the material and the measurement of their reflectance spectra from the visible portion through the infrared portions of the electromagnetic spectrum. Every pixel in the image have a continuous spectrum in reflectance or radiance (Qiu et al. 2017). Because of the continuous spectrum, technique has several geological uses, such as the identification and characterization of mineralogical alteration assemblages (Tappert et al. 2015; Mathieu et al. 2017), correlation between different geological units (Dorador and Rodriquez-Tovar 2016), and identification of faults and fractures, and evaluation of the degree of veining or dissemination (Qu et al. 2016). From drill cores, hyperspectral imaging can provide an extensive and reusable digital data. This data can be used to help to understand the geology of a certain area and has benefits in geological surveying and mining work (Tappert et al. 2015; Mathieu et al. 2017). Nowadays, airborne hyperspectral imaging is used for e.g. comparison of lithological mapping results (Feng et al. 2017).

In hyperspectral imaging, different wavelengths are used to recognize different minerals (Table 2). In visible to near infrared (VNIR) wavelengths, iron oxides can be identified, but with other minerals the identifying ability of VNIR is limited. Although, VNIR produces useful information by used with other wavelengths. In short wave infrared (SWIR) wavelengths chlorite, micas, clay minerals, and carbonites can be identified. In long wave infrared (LWIR) wavelengths, it is possible to distinguish most of the silicate minerals. Some of the ore minerals, mostly sulphides and oxides, do not have hyperspectral response (TerraCore 2018a), but pathfinder minerals may be used in study of those minerals (Seitsaari 2016).

Table 2. Minerals and identification ability of different hyperspectral wavelengths (Data provided by TerraCore).

	Structure	Group	Example	VNIR Response	SWIR Response	LWIR Response
Silicate	Inosilicates	Amphibole	Actinolite	Non-diagnostic	Good	Good
		Pyroxene	Diopside	Good	Moderate	Good
	Cyclosilicate	Tourmaline	Dravite	Non-diagnostic	Good	Moderate
	Nesosilicates	Garnet	Andradite	Moderate	Non-diagnostic	Good
		Olivine	Forsterite	Good	Non-diagnostic	Good
		Zircon	Zircon	Good	Non-diagnostic	Non-diagnostic
	Sorosilicates	Epidote	Clinozoisite	Non-diagnostic	Good	Good
	Phyllosilicates	Mica	Muscovite	Non-diagnostic	Good	Moderate
		Chlorite	Clinochlore	Non-diagnostic	Good	Moderate
		Clay Minerals	Kaolinite	Non-diagnostic	Good	Moderate
			Illite	Non-diagnostic	Good	Moderate
	Tectosilicates	Feldspar	Orthoclase	Non-diagnostic	Non-diagnostic	Good
			Albite	Non-diagnostic	Non-diagnostic	Good
		Silica	Quartz	Non-diagnostic	Non-diagnostic	Good
Non-silicate	Carbonates	Calcite		Non-diagnostic	Good	Good
		Dolomite		Non-diagnostic	Good	Good
	Hydroxides	Gibbsite		Non-diagnostic	Good	Moderate
	Sulphates	Alunite	Alunite	Non-diagnostic	Good	Moderate
			Barite	Non-diagnostic	Non-diagnostic	Good
	Borates		Borax	Non-diagnostic	Good	Uncertain
	Halides	Chlorides	Halite	Non-diagnostic	Moderate	Uncertain
	Phosphates	Apatite	Apatite	Moderate	Moderate	Good
			Amblygonite	Moderate	Good	Good
	Hydrocarbon		Bitumen	Non-diagnostic	Good	Uncertain
	Oxides		Hematite	Good	Non-diagnostic	Non-diagnostic
		Spinel	Magnetite	Non-diagnostic	Non-diagnostic	Non-diagnostic
	Sulphides		Pyrite	Non-diagnostic	Non-diagnostic	Non-diagnostic

3.6 Estimation of mineral resources and ore reserves

Mineral resources and ore reserves are estimations of tonnage and grade of the deposit represented three dimensionally. Variation in density of sampling and limited mine workings are taken into consideration in resource and reserve estimations. The estimations are based on certain interpretations and assumptions of continuity, shape and grade of the deposit (Haldar 2012).

Mineral resources are the in situ natural concentration or occurrence of mineralization locating in a geologically defined area. The geological features, e.g. quantity, grade, and continuity, are partly known, estimated, or interpreted from a wide base of indications and regional knowledge. The ore reserve is well-defined part of the deposit that is explored in detail and have a specific cut-off. In the reserve estimation, there must be a high-level confidence based on reliable and detailed information. Geological and grade continuity is confirmed by sample locations which are spaced closely enough (Haldar 2012).

In upgrading resources to reserves there are several factors which must be taken into consideration. Cut-off grade is a most significant relative economic factor for calculation of resource and reserve from exploration data. It is determined as boundary between low-grade mineralization and techno-economically viable ore. Cut-off grade is influenced by for example operating costs, deposit size, and cutting factors. (Haldar 2012).

Conventional and geostatistical approaches for the resource and reserve estimations are introduced below.

3.6.1 Conventional estimation

Generally, conventional estimations methods are depending on the shape, dimension, complexity of the deposit, and sample type and interval during exploration. If an intricate deposit has a large volume of sample information, the procedures are complex. The conventional methods are listed in Chapter 8 – Mineral Resource and Ore Reserve Estimation in the book Mineral Exploration – Principles and Applications written by S.K. Haldar (2012).

Conventional estimations are done by calculations, which take into consideration several factors that were mentioned in section 3.6. There is collection of some equations below for calculating average grade of the deposit. Same equations are used in the sorting index calculations. According to Haldar (2012), potential of mineral resource or ore reserve of the deposit is estimated traditionally by straightforward equation (1) with minor variation:

$$t = V \times SG \tag{1}$$

$$V = A \times influence\ of\ third\ dimension$$

$$Total\ T = \sum_{i=1}^{n}(t_1 + t_2 + t_3 \dots t_n)$$

where, t_n or T is measured quantity in metric tonne, SG is specific gravity, V is volume in cubic metres (m^3), and A is area in square metres (m^2) that is derived by measurements from plans or sections of the geologically defined mineralized deposit area.

Composite grade of an intercept along a channel or borehole can be calculated by the equation (2):

$$g = \sum(l_1 \times g_1 + l_2 \times g_2 \dots + l_n \times g_n) / \sum_{i=1}^{n}(l_1 + l_2 \dots + l_n) \tag{2}$$

where, g_n is grade of a sample and l_n is a length of a sample.

Average grade of section, plan, orebody, and deposit is calculated by the equation (3):

$$g = \sum(t_1 \times g_1 + t_2 \times g_2 \dots + t_n \times g_n) / \sum(t_1 + t_2 \dots + t_n) \qquad (3)$$

where, g_n is a grade of sub block and t_n is tonnes of sub block.

Conventional estimations are developed based on spatial position and value of surrounding ground and there is no objective way to measure the reliability of the estimation. Use of conventional methods can cause of passing a profitable deposit, while uneconomic deposits may be overvalued (Haldar 2012).

3.6.2 Geostatistical estimation

Nowadays, the resource and reserve estimations are mainly done by using geostatistics. Geostatistics is formed by borrowing techniques from formal statistical theory. Borrowed techniques include sample mean, range, standard deviation, variance, frequency distribution, histogram plot, correlation coefficients, analysis of variance, t-test and f-test, trend analysis and distance inverse for univariate and multivariate elements. The classical statistical methods do not include the inherent geological variance within the deposit and disregards spatial relationships but assume that sample values are randomly distributed, and they are independent of each other. Applications in geostatistics are developed to resolve this problem (Haldar 2012). Nowadays, there are several software applications in the mining industry, e.g. Surpac, which can calculate the resource and reserve estimations straight from the drill core data by using geostatistics.

Semi-variogram is a way to compare values by considering their differences, for example, in grade between two points. The simplest semi-variogram calculation can be done by sliding mineralization in one direction along a borehole (Haldar 2012).

Semi-variogram has properties including the continuity and the nugget effect. The continuity is projected by the rate of growth of $\gamma(h)$ for small value of h. The growth curve is expressing the regionalized element of the sample. If the increase is steady and smooth, it is indicating good continuity of mineralization till it flatten in some distance. That is also known as the structured variance. The semi-variogram value without separation distance (lag=0) is theoretically 0. In many cases, the value is over 0. A nugget effect increases the semi-variogram values at an infinitely small separation distance. For example, in precious metal deposits, metals can exhibit a very high nugget effect even up to total inexplicable variance. That creates a lot of uncertainty in continuity of mineralization and estimation of grade, and can lead to unreasonable sampling (Haldar 2012).

Kriging is an application of geostatistics that is developed to the valuation and optimization of ore. Point and block kriging is used to value estimation of a point or block. Semi-variogram is a precondition of kriging estimate. The precision factor of semi-variogram is in large extent proportional to the kriging estimation, and a point kriging is suggested to be a test for a semi-variogram model (Haldar 2012).

According to Haldar (2012), benefits of the geostatistics are broad. The statistical methods are providing a lot of parameters at any stage for sequential analysis of exploration term. Variogram takes into consideration nature of the deposit (isotropic or anisotropic), and the variance of orebody. Error in variance can be minimized by the best linear unbiased estimate (BLUE) method and estimations errors can be calculated geostatistically. In planning of selective mining and grade control, estimated average grade and tonnage of each blocks are important information. With geostatistics is also possible to optimize sampling design, and analysis of estimated and actual performances of a mine (Haldar 2012).

3.6.3 Classification systems

There are several mineral resource and ore reserve classification systems and reporting codes. Basis of the schemes and codes is in geological confidence, convenience to use, and investment need in mineral sector. In worldwide, there are classification schemes and reporting codes such as USGS/USBM reserve classification scheme (USA), United Nations Framework Classification (UNFC) system, Joint Ore Reserve Committee (JORC) code (Australia and New Zealand), Canadian Institute of Mining, Metallurgy and Petroleum (CIM) classification, South African Code for the Reporting of Mineral Resources and Mineral Reserves (SAMREC), and The Reporting Code (UK) (Haldar 2012).

Resources and reserves of spodumene pegmatite deposits in Kaustinen area are classified by competent persons of the JORC 2012 code. The JORC code is prepared by the Joint Ore Reserve Committee of The Australasian Institute of Mining and Metallurgy (The AusIMM), Australian Institute of Geoscientists (AIG), and Minerals Council of Australia (JORC 2012).

Transparency, essentiality and competence are the principles governing of the operation and the application of the JORC Code. Transparency requires that public reports must have sufficient information with clear and unambiguous presentation. Papers must be easy to understand, and information cannot be misleading. Essentiality requires that all the relevant information that investors and their professional advisers would reasonably require and expect to find is in the public report. They must be able to do a reasoned and balanced judgement regarding exploration results, mineral resources or ore reserves, which are reported. Competence requires that the public report is based on responsible and enforceable work done by suitably qualified professionals. Terms which have to be used in the public reports dealing with exploration results, resources or reserves are set out in Figure 3. Figure 3 also outlines framework for classifying grade and tonnage estimations which are reflecting from different levels of geological confidence and different degrees of technical and economical evaluation (JORC 2012).

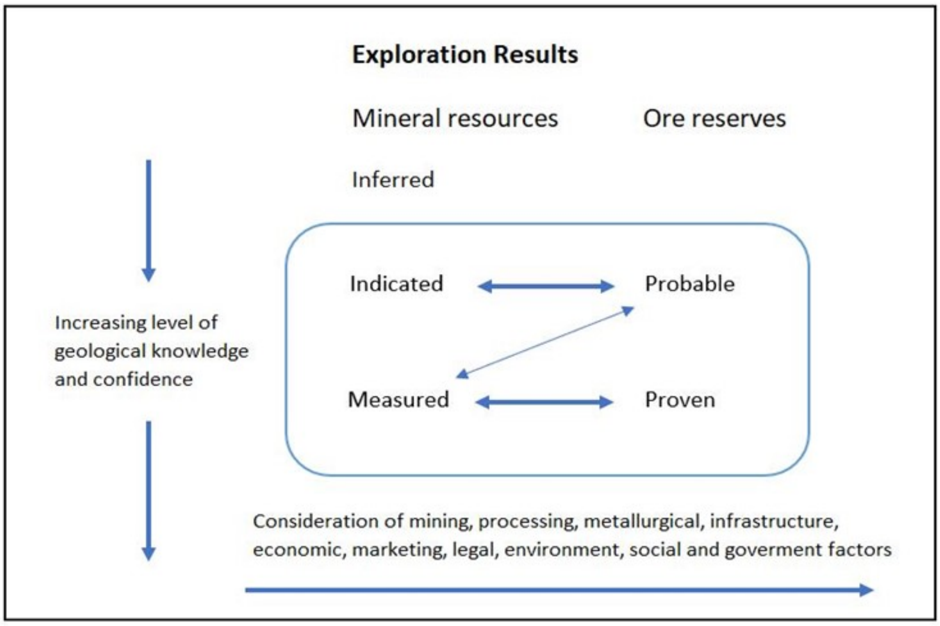


Figure 3. Relationships between exploration results, mineral resources, and ore reserves which are basis of the JORC Code (Modified after JORC 2012).

4 MATERIAL AND METHODS

4.1 The starting point for the study

The aim of the study is the development of an index, that can be used in estimation of waste rock dilution. The starting point for the study is to define which mine blocks do need sorting and which ones do not. It is found in geometallurgical studies, the black waste rock cause problems in flotation of spodumene by lowering recovery and head-grade (Salvador 2017). Therefore, it is important to get waste rock dilution as low as it is possible.

There are external and internal waste rock dilution. The external dilution is possible separate by mining, but SBS is needed to use in separation of internal dilution out of the feed. The sorting need is depending on waste rock dilution of the block. For example, there can be three different ore feeds to jaw crusher: one with low, second with medium and third with high waste rock dilution. In case of Keliber, this could mean processing of the ores in three different ways as shown in Figure 4. Ore having low waste rock dilution, say less than 5 %, does not require sorting after crushing, and so coarse material and fines can be transported straight further in the process. Ore, that has medium waste rock dilution, say between 5 % and 20 %, requires SBS. Accepted material from sorting and fines of medium diluted ore can be processed further. Ore with high waste rock dilution, say more than 20 %, is processed differently after crushing, screening and sorting. Accepted particles of highly diluted ore go further in process while rejected particles and fines go to the dump site.

The purpose of this work is to create a procedure how data should be collected and utilized in lithium ores to find out, if such a processing is economically feasible and what is needed to define the dilution percentage boundaries for different ore bodies.

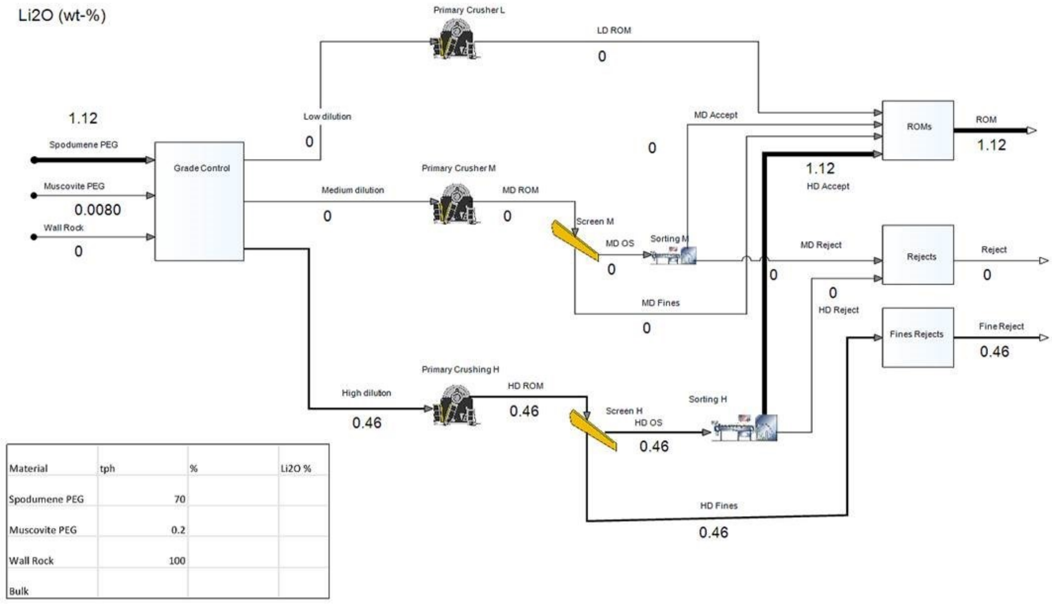


Figure 4. Paths of ore with different wall rock dilutions.

4.2 Material

Rapasaari ore was selected as a case study because it contains several parallel spodumene pegmatite dikes, which in flotation test the waste rock dilution have been found to have significant negative impact for processability and being the biggest ore body of Keliber there are several different alternatives for applying sorting, as shown in Figure 4. A set of 28 drill cores (ca. 800 metres) from the Rapasaari deposit were selected for relogging. Drill cores were drilled by Oy KATI Ab with machinery WL-66. The diameter of drill core was 50.5 mm. The developed sorting index is based on relogged drill cores. All drill cores were chosen from drilling profiles that include spodumene pegmatite intercepts from the same spodumene pegmatite dike (Figure 5). Mineral resource estimate has been made for the dike enabling comparison between the estimated resources and resources calculated by using sorting index. This comparison also makes possible to verify functionality of the sorting index.

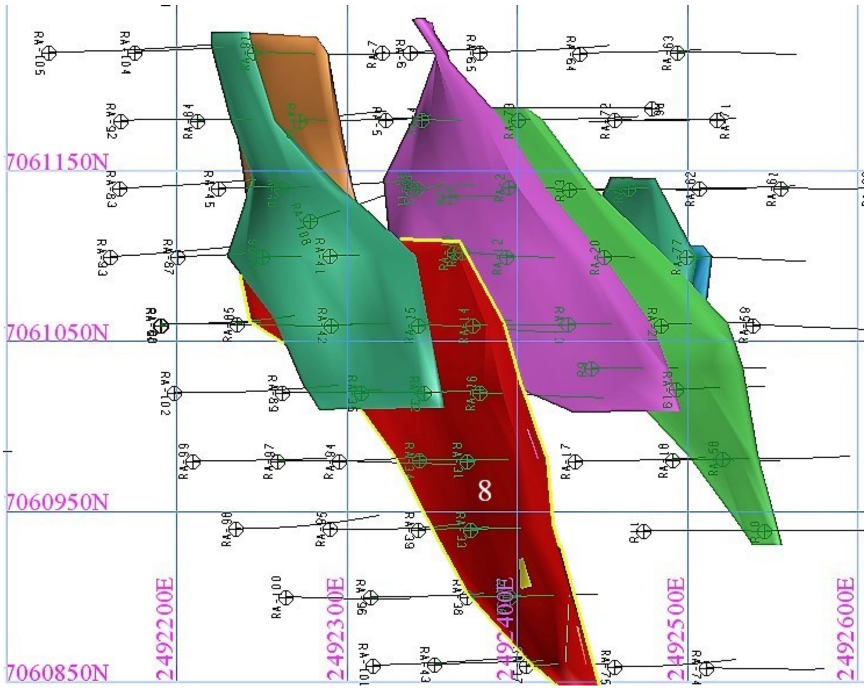


Figure 5. Drill cores related to highlighted ore dike, solid number 8, were relogged.

Samples for bench-scale sorting test were collected from ore piles of Syväjärvi and Länttä test pits. Samples included pieces of spodumene pegmatite with different grades, muscovite pegmatite (barren), albite-quartz pegmatite (barren), and black waste rock. Diameter of samples was ca. 10 cm. Also 15 pieces of drill core halves were chosen from the Rapasaari deposit. Objective of the test was to develop and demonstrate the separation of spodumene pegmatite and barren pegmatite. Rejecting of barren pegmatite from the process feed may enable significant savings in downstream process by lowering comminution costs and increasing the head grade of flotation feed.

Every sample were grouped and numbered for identification. Sample grouping was performed by macroscopic study and estimation of spodumene grade of each sample. Diameter of samples were ca. 10 cm. As shown in Table 3, samples 1 to 53 were pegmatite samples from the Syväjärvi deposit and samples 54-79 were pegmatite samples from the Länttä deposit. Samples 79-85 were black waste rock samples: 79-82 were mafic metavolcanic rock samples from the Länttä deposit and samples 83-85 were plagioclase porphyrite samples from the Syväjärvi deposit. Samples 86-100 were halved drill core pieces from the Rapasaari deposit. Composite grades for sample groups were received by collecting group sample from each group. Samples were digested with four acid digestion and analysed with inductively coupled plasma optical emission spectrometry (ICP-OES) in laboratory of Labtium in Kuopio.

Table 3. Sample IDs, groups, deposits, and classification of each sample group.

Sample ID	Group	Deposit	Classification	Li_2O %
1-5	High-grade spodumene pegmatite	Syväjärvi	Spodumene content >25%	3.12
6-13	Medium-grade spodumene pegmatite	Syväjärvi	Spodumene content 15-25%	2.20
14-24	Low-grade spodumene pegmatite	Syväjärvi	Spodumene content 8-15%	1.57
25-35	Spodumene pegmatite below cut-off	Syväjärvi	Spodumene content <8%	0.79
36-53	Barren pegmatite	Syväjärvi	Qtz-ab(-mus-Kfs)	0.43
54-70	Länttä spodumene pegmatite	Länttä	Reddish and greenish spodumene >8%	1.48
71-79	Länttä barren pegmatite	Länttä	Qtz-Ab-Kfs(-Mus)	0.33
80-85	Black waste rock	Syväjärvi, Länttä	Syväjärvi: Plagioclase porphyrite; Länttä: Amfibolite	0.15
86-100	Halved drill core	Rapasaari	Muscovite pegmatite pieces, Qtz-ab pegmatites, and spodumene pegmatite pieces	

Each sample and sample group were photographed both dry and wet. Samples and sample groups from the Syväjärvi deposit are shown in Figure 6.

Figure 6. Sample groups to the bench-scale sorting test from the Syväjärvi deposit.

4.2.1 Mineralogy of the samples

Mineralogy of the pegmatite samples varies only in terms of mineral mass proportion. For support of macroscopic classification and for proving lack of variation, polished thin sections with thickness of 30 µm were done from 11 samples for microscopic study. The microscopic study was carried out with polarization microscope. Comparison of refractive indexes of minerals and pleochroism was determined with one polarizer. Other features were determined through crossed polarizers. Minerals found and some of their properties are listed below (Table 4).

Table 4. Main minerals found, and their optical properties used for identification

Mineral	Formula	Properties
Spodumene	$LiAlSi_2O_6$	Biaxial (+); 2V=60°; Max. Birefringence 0.020; High surface relief; Extinction angle 24°
Albite	$NaAlSi_3O_8$	Biaxial (+); 2V=80°; Max. Birefringence 0.009; Low surface relief; Twinning
Quartz	SiO_2	Uniaxial (+); Max. Birefringence 0.009; low surface relief
K-feldspar	$KAlSi_3O_8$	Biaxial (-); 2V=80°; Max. Birefringence 0.007; Low surface relief
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	Biaxial (-); 2V=40°; Max. Birefringence 0.036; Moderate surface relief; Straight extinction towards 001-cleavage
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	Uniaxial (-); Birefringence 0.006; High surface relief, Straigth extinction.

Mineral compositions have minor variation between studied pegmatite ore thin sections reflecting in the classification. When spodumene grade is high, the amounts of albite and quartz is low and vice versa. Also, the muscovite occurrence has variation. In spodumene pegmatite, it occurs both primary and secondary muscovite. Primary muscovite has euhedral crystal form and occurs apart from spodumene crystals. Secondary muscovite occurs in margins of spodumene crystals (Figure 7) showing alteration of spodumene. Alteration is not seen within all spodumene crystals. Apatite is accessory mineral with quantity of less than 1 %.

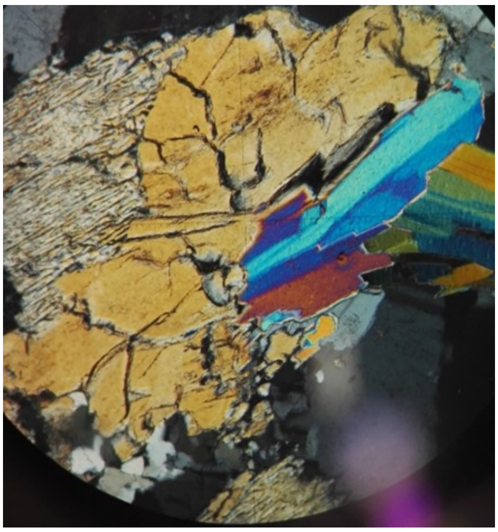


Figure 7. Muscovite (blue/reddish) associated with spodumene crystal (orange). Diameter of view is 5 mm.

Salvador (2017) conducted MLA-studies and defined the average mineral composition of spodumene pegmatites for different deposits based on representative bulk samples (Table 5). Compositions have variation, depending the amount of spodumene. The Syväjärvi deposit has the highest spodumene and muscovite grade, and therefore the lowest albite grade. The Rapasaari deposit has the lowest spodumene content with the highest quartz content. Spodumene pegmatite of the Länttä deposit has the highest quantity of mafic silicates including amphibole, biotite and tourmaline. The mass proportion and nature of mafic silicates is probably related to the nature of country rock of the deposit.

Table 5. Modal compositions (weigth percentages) of spodumene pegmatite for three different deposits (Salvador 2017).

	Syväjärvi	Länttä	Rapasaari
Spodumene wt%	18.3	16.6	13.8
Quartz wt%	27.8	25.9	28.1
Albite wt%	30.7	34.2	33.6
K-feldspar wt%	12.7	13.1	13.6
Muscovite wt%	6.8	3.9	4.9
Apatite wt%	0.4	0.5	0.2
Mafic silicates wt%	1.9	4.3	3.6

Country rocks of the different deposits vary. Main country rock in Syväjärvi is plagioclase porphyrite, which is composed of mainly plagioclase (47 %), amphiboles (19 %), biotite (19%) and quartz (9 %) with several accessory minerals. Amphibolite in Länttä contains amphiboles (40 %), plagioclase (33 %), biotite (8 %), epidote and quartz (6 % each) with tourmaline and other mafic minerals. Tourmaline seam at the margin of spodumene pegmatite contains tourmaline (45 %), quartz (13 %), biotite (14 %), and muscovite (10 %) with several other minerals. Main country rock of the Rapasaari deposit is mica schist. Mica schist mainly contains biotite (35 %), quartz (30 %), muscovite (15 %) and plagioclase (14 %) (Lamberg 2018).

4.3 Drill core relogging

Drill core relogging was recorded to a Keliber Oy logging sheet with few modifications. All drill cores were previously logged by geologists of the company. Most of the relogging was carried out from high quality drill core pictures. Differences between the original logging and relogging were logged with more precision near pegmatite dikes with extra features. In Appendix 1 is a relog of one of the drill cores. Relogging procedure is described below.

Depths (from-to), lengths, core loss, lithology, structural features, weathering, and features of spodumene pegmatite were determined from drill cores as geologists were previously logged. Also, structural features' angle towards drill core (CA - core angle) and assay id were written as they did exist in original data. Modified part includes percentages of spodumene pegmatite (SPG %), barren pegmatite (White %), and black waste rock (Black %) in each drill core intervals with contact type code (C-type) for pegmatites. SPG % included only spodumene bearing pegmatite, white % included muscovite pegmatite, K-feldspar and quartz-albite pegmatite, and black % included all dark waste rocks with all origins, for example plagioclase porphyrite and mica schist. Table 6 shows logged features.

Table 6. Relogged features and their notation in drill core relogging

Logged Feature	Numerical	Alphabetical
Depths and lengths of interval	Rounded off the nearest 5 cm	
Rock code		Abbreviation of rock type
Structure code		Abbreviation of structure
Weathering code	1-5	
Spodumene angle, core angle	Features angle towards drill core	
Amount of spodumene, spodumene pegmatite, barren pegmatite and black barren	Percentage of drill core interval	
Contact type code	1-4	
Assay ID	Consecutive number	

As previously stated, optical sensor-based sorting is based on colour contrast between ore and waste rock. The percentages of spodumene pegmatite, barren pegmatite, and black waste rock are estimated alike. Estimations are presented as percentages in the drill core interval like the rock quality designation in geotechnical logging. These percentages are used for modelling the sorting result. Estimation calculations of Li_2O grade can be done for unsorted and sorted material when assay results are known. More about these calculations and sorting modelling is described in the next chapter. In Figure 8, there is an example of internal mica schist part from 128.70 m to 129.80 m in high grade spodumene pegmatite ore. Mica schist includes 10 centimetres long part of spodumene pegmatite and 5 cm piece of barren pegmatite. In drill core relogging 10 cm and longer parts of pegmatite inside wall rock were logged as their own units.

Figure 8. An intercept of spodumene pegmatite with internal waste rock.

Contact types were defined for estimation of liberation of pegmatite particles and to aid defining the thresholds of SBS machine. After blasting and crushing material from near ore/waste rock contacts, there is a possibility that spodumene pegmatite contact material include black waste rock. In that case threshold of SBS machine should be reconsidered: is it better to have higher waste rock dilution in process or is the spodumene loss economically insignificant. Four different contact types were defined in this study and they were marked with a code number (Figure 9): contact type code 1 is a closed contact without spodumene nearby (Fig. 9A), contact type code 2 is an open contact without spodumene nearby (Fig. 9B), contact type code 3 is a closed contact with spodumene nearby (Fig. 9C), and contact type code 4 is an open contact with spodumene nearby (Fig. 9D). If pegmatite did not have spodumene grains within 10 centimetres from wall rock contact, the contact was defined to be without spodumene and had contact type code 1 or 2. The code 3 or 4 was used when spodumene occurred within 10 cm from the wall rock contact. Contact codes were defined for wall rock inclusions inside spodumene pegmatite intercepts too. A wall rock type did not affect to contact type codes.

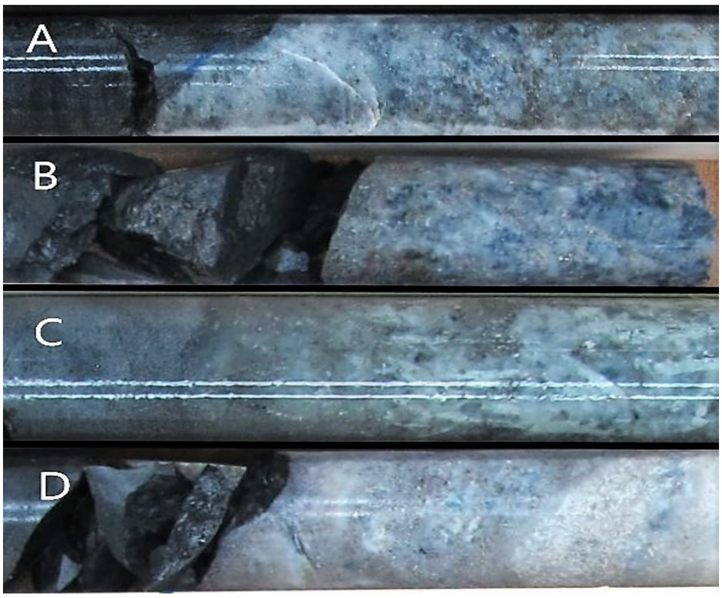


Figure 9. Contact types: A. Closed contact without spodumene nearby; B. Open contact without spodumene nearby; C. Closed contact with spodumene nearby; D. Open contact with spodumene nearby.

4.4 Sorting index calculations from drill cores

Sorting index calculations are based on data from relogged drill cores. Calculations were done for modelling the sorting result assuming that the sorter ability to separate black and white rocks is 100 percent. Pieces of spodumene pegmatite and barren pegmatite are assumed to be accepted by the sorter. Assumption was based on result of the sorting test of Keliber Oy.

Calculations were performed for each drill core separately. Drill depths, lengths, lithology and contact type codes were copied from relogging sheets (Table 7). Li_2O total grade was collected from assay files of the Rapasaari deposit. For the rock units, which were not taken into resources estimations, the lithium oxide grades were marked to be -1. In Li_2O interpretation grades -1 values were replaced by value 0.2 % that is an average grade in wall rock near the spodumene pegmatite contacts. The replaced value is used for estimation of losses in recovery of total lithium. There were some under 40 cm long spodumene pegmatite or barren pegmatite intercepts without assay conducted. In those cases, used Li_2O grades were 0.8 % to spodumene pegmatite intercepts and 0.002 % to barren pegmatite intercepts. 0.8 % is the median grade of all pegmatite assays, including both spodumene and barren pegmatite assays, of drilling programme of Keliber Oy in year 2016. A lithium oxide grade of 0.002 % was the minimum grade for the barren pegmatite in the same drilling programme.

Table 7. Calculation example from one of the drill cores. Lithology: KL = mica schist; SPG = spodumene pegmatite; MPG = (muscovite) barren pegmatite; PP = plagioclase porphyrite.

Hole id	from	to	length	lithology	Li2O tot	Li2O interpr.	White ore%	White barren%	Black waste%	ore length	white length	black length	C-type
RA-14	11	11,6	0,60	SPG	1,858	1,858039	100	0	0	0,60	0,00	0,00	
RA-14	11,6	13,7	2,10	SPG	1,143	1,143243	100	0	0	2,10	0,00	0,00	
RA-14	13,7	16,7	3,00	SPG	1,137	1,136784	100	0	0	3,00	0,00	0,00	
RA-14	16,7	19,4	2,70	SPG	1,343	1,343472	100	0	0	2,70	0,00	0,00	
RA-14	19,4	20,05	0,65	SPG	0,332	0,331562	20	80	0	0,13	0,52	0,00	2
RA-14	20,05	21,05	1,00	PP	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-14	21,05	22,05	1,00	PP	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-14	22,05	23	0,95	PP	-1	0,2	0	0	100	0,00	0,00	0,95	
RA-14	23	24	1,00	KL	-1	0,2	0	12	88	0,00	0,12	0,88	
RA-14	24	25	1,00	KL	-1	0,2	0	5	95	0,00	0,05	0,95	
			14,00							8,53	0,69	4,78	
										60,93 %	4,93 %	34,14 %	

Table 7 demonstrates how the percentages for spodumene pegmatite (white ore), barren pegmatite (white barren) and waste rock as they were determined in relogging. These percentages were used for calculation of lengths of each unit in drill core intervals. With calculated lengths sorting result was estimated by acceptance and rejection percentages.

Grades and lengths of drill core intercepts were used to composite grade calculations of each drill core. Equation (2) was used in these calculations. With these calculations it is possible to estimate grade for accepted and rejected material before and after sorting process. Estimations are based only on drill core data. Appendix 2 includes the sorting index calculation for a drill core.

4.5 Sorting index in blocks

Sorting index in blocks is related to rock types and their volumes in a block. Equation (3) is used to calculate tonnes of a block by conventional method. Specific gravity (SG) of spodumene pegmatites is in practice depending on the amount of spodumene. Spodumene is having SG of 3.15 when quartz and feldspars are having 2.6-2.7. SG of ore grade spodumene pegmatite is varying between 2.65 and 2.8 (Keliber 2016).

In this study, a block model was made with attributes for barren pegmatite and black waste rock, including the sorting index values. The block model was done by professional of JORC Code. The software used was GEOVIA Surpac. Used block size was 10 m x 5 m x 5 m. In the block model, 1 m composites were used for index values of black waste rock and barren pegmatite. Number of samples was 310 in both estimations (Loven 2018). For block value estimation, the used geostatistical interpolation method was inverse distance. The inverse distance method is weighting the nearest known index values of each point to estimate values for unknown points.

4.6 Bench-scale sorting test

Bench-scale sorting test was executed with four different sensor systems: Colour camera (COLOR), Near-infrared spectrometry (NIR), X-ray transmission (XRT), and multi-channel Laser (LASER). Separation potential of each sensor was defined especially for separation of spodumene and barren pegmatite.

Each individual sample was examined separately through sensors, except with the XRT-sensor the samples were taped on sheets in numerical order and then examined. All examined samples were washed before analysis, except with the XRT. In SBS analyses based on optical properties, the feed in whole should be either dry or wet providing feed with similar optical properties for the sorting machine. The XRT is based on atomic densities of the sorted material. Therefore, feed’s wetness, and in this case sheets’ light plastic, does not affect to the sorting result.

From sample groups, high-, medium, and low-grade spodumene pegmatite samples, and Länttä SPG samples were classified as product. Spodumene pegmatite below cut-off, barren pegmatites from the Syväjärvi and Länttä deposits, and black waste rock were classified as waste. Sorting test results are reported by using that classification.

4.7 Hyperspectral imaging

Hyperspectral imaging was done by TerraCore. The system included three different cameras: a high resolution natural-colour camera (RGB), a coupled visible-near infrared (VNIR) and short-wave infrared (SWIR) camera, and long-wave infrared (LWIR) camera. The covered wavelength range from the electromagnetic spectrum was 380-2500 nm and 7700-12300 nm. Pixel size of VNIR-SWIR and LWIR camera was 1 mm. RGB camera had the pixel size of 0.16 mm (TerraCore 2018).

Studied drill cores were from five different deposits totalling circa 280 metres. In this study focus is in drill cores of the Rapasaari deposit. Drill cores RA-86 and RA-88 were included in the sorting index calculations. Particularly mineralogy of the drill cores within pegmatite intercepts was focused. Another focal point was to see alteration of spodumene and lithium halo in country rocks, which related to another study.

5 RESULTS

5.1 Relogging

Relationships of different rock types were possible to define during drill core relogging. The studied spodumene pegmatite dike was homogenous for the most part, but slight zonation is possible to distinguish from drill core data (Figure 10). In several drill cores, there were barren pegmatite or alteration zones near contacts. In these zones, spodumene was lacking or altered to muscovite. Percentage of altered pegmatite was increasing toward tips of the dike when thickness of the dike was decreasing. However, in some drill cores there were not altered or barren zones. The thickness of the zone was varying from 0 to about 1 metre. Average thickness of the zone was 30-40 centimetres. Amount of black waste rock was increasing close to the contact zone in some parts of the dike. There are also narrow parallel pegmatite veins in some parts of the main dike. Distance between mentioned veins and main dike was varying from 1 to 3 metres and the gap was black waste rock. Narrow veins with greater distance from the main dike are too far to be exploited.

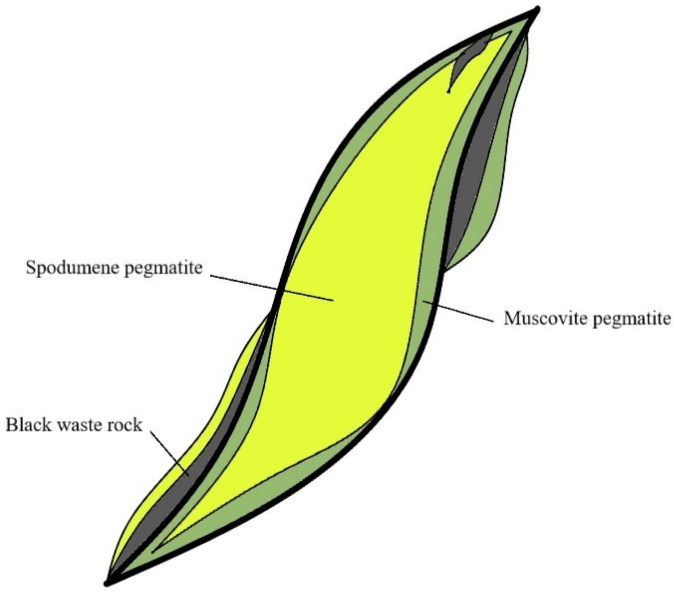


Figure 10. Sketch of intersection of spodumene pegmatite dike with narrow parallel pegmatite veins.

It was interpreted that there are two kinds of internal black waste rock inclusions. Smaller black waste rock units have formed during the formation of pegmatite dikes. These units are not continuous. They were formed when pegmatite melt intruded to fractures of country rocks taking along country rock pieces. Larger internal waste rock units were formed, when several parallel fractures were filled with pegmatite melt. Waste rock units were surrounded by pegmatite melt. Those waste rock units can be followed from a one drilling profile to another profile. Vertical continuity can be several tens of metres in a profile.

When contact type data was examined, it was found that one contact type contributes over two thirds of all the contacts. Those are closed contacts, without spodumene nearby, the contact type code 1 (Figure 11). To much lesser extent, there were also several closed contacts with spodumene nearby, the contact type code 3. Open contacts were rarer and relating mostly to weathered pegmatites near surface. In those weathered parts, spodumene was more often altered to pseudomorphs causing lower lithium grade.

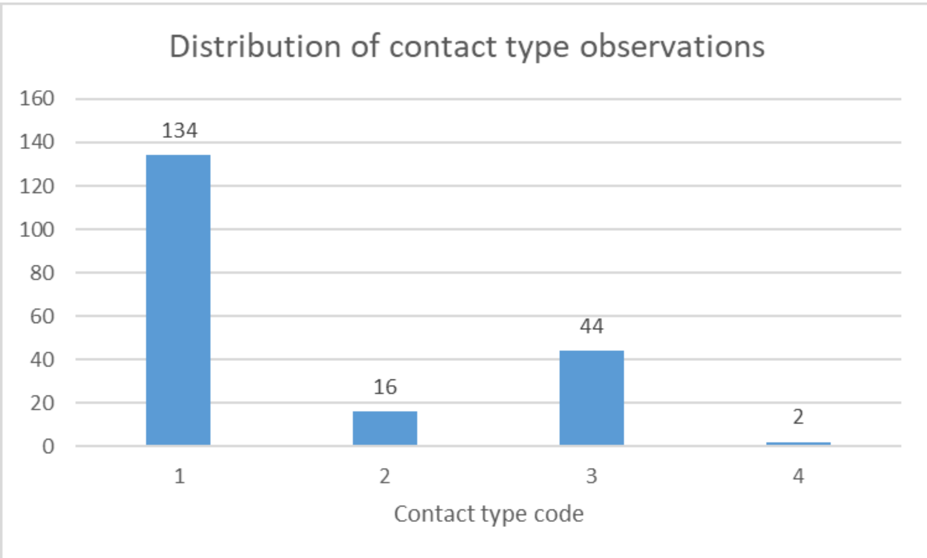


Figure 11. Distribution of contact type observations in relogged drill cores.

5.2 Waste rock modelling

In this study internal waste rock modelling was done by two different ways. One method is sorting index calculations from relogged drill core data as it is previously described. Another method is Surpac solid model of internal waste rock parts based on original drill core data. Solid model was created for comparison to calculated model.

5.2.1 Sorting index calculations from drill core data

In this modelling, only internal waste rocks were included in calculations making comparison with Surpac solid model possible. Spodumene pegmatite intervals, which are close to main dike and are to be considered as mineable material, were included in intercepts. Those included internal waste rock interval raised amount of black waste rock in calculations.

The amount of black waste rock was depending on location of ore intercept in spodumene pegmatite dike. In the middle part of the dike there was no internal waste rock. The amount was increasing near contacts and endings of the dike.

The results from the sorting index calculation are presented in Table 8. Waste rock dilution of the dike was varying between 0 % and 53 %. Same percentages can be assumed to be rejected by SBS. Although, with the low and medium-diluted ore, some of the waste rock is passing sorting process as fines. Large variation of waste rock dilution is explained by assumption of smaller spodumene pegmatite veins near the main dike within the calculations. In these cases, the lengths of wall rock between spodumene pegmatites were from 2 to 4 metres. Composite grades were weighted as average grades for each pegmatite intercept including both spodumene bearing and barren pegmatites. These grades are assumed to be grades of sorted material without wall rock dilution. Amount of material that sorter can separate as product can be calculated by subtracting amount of black waste rock from 100 percent.

Table 8. Amount of black waste rock and barren pegmatite in each spodumene pegmatite intercept with composite Li_2O grade. Material assumed to be rejected by sorter is marked with red font and accepted by green font.

Drill core	Intercept (SPG+Barren)		% in length of Intercept	
	Length (m)	Composite Li2O %	Black waste	Barren pg.
RA-10	5.35	0.65	0 %	0 %
RA-14	9.05	1.20	0 %	6 %
RA-15	11.75	0.82	9 %	26 %
RA-16	11.45	1.39	0 %	3 %
RA-31	14.5	1.14	0 %	32 %
RA-32	11.35	0.67	1 %	44 %
RA-33	19.6	0.99	17 %	31 %
RA-34	14.0	1.15	7 %	12 %
RA-35	24.85	1.22	24 %	19 %
RA-36	3.7	1.65	0 %	14 %
RA-37	28.2	1.35	23 %	14 %
RA-38	7.0	1.46	0 %	16 %
RA-39	15.2	0.96	7 %	9 %
RA-41	7.65	0.97	20 %	22 %
RA-42	18.9	1.21	32 %	5 %
RA-43	5.25	1.40	10 %	0 %
RA-85	4.6	1.07	1 %	41 %
RA-86	10.2	0.91	0 %	18 %
RA-87	19.8	1.41	5 %	3 %
RA-88	8.05	1.01	22 %	0 %
RA-89	13.75	1.24	17 %	8 %
RA-90	4.85	1.62	53 %	9 %
RA-93	13.35	1.41	37 %	9 %
RA-94	11.8	0.94	2 %	26 %
RA-95	25.3	1.29	23 %	6 %
RA-96	13.85	0.90	0 %	14 %
RA-97	19.25	1.24	23 %	4 %
RA-101	7.0	1.00	32 %	8 %
Weighted average:		1.16	15 %	14 %

Amount of barren pegmatite is varying from 0 to 44 percent. As seen in Figure 10, the amount depends on location of intercept in spodumene pegmatite dike: in the most cases percentage is larger at near contacts and tips of the dike than in the middle parts of the dike.

5.2.2 Surpac modelling of internal waste rocks

Internal waste rocks including barren pegmatite and black waste rocks are modelled as solids in Surpac. Modelling required continuity of waste rock unit between drilling profiles. Eight solids were possible to model for internal waste rocks (Figure 12). Internal solids with number of 7.1 and 7.2, 8, 9, 14 and 15 were black waste rocks including mica schist or plagioclase porphyrite. Solids 24 and 25 were barren pegmatite, mainly muscovite pegmatite. Primary and secondary muscovite are not separated. There are included narrow spodumene pegmatite parts in some of the waste rock solids.

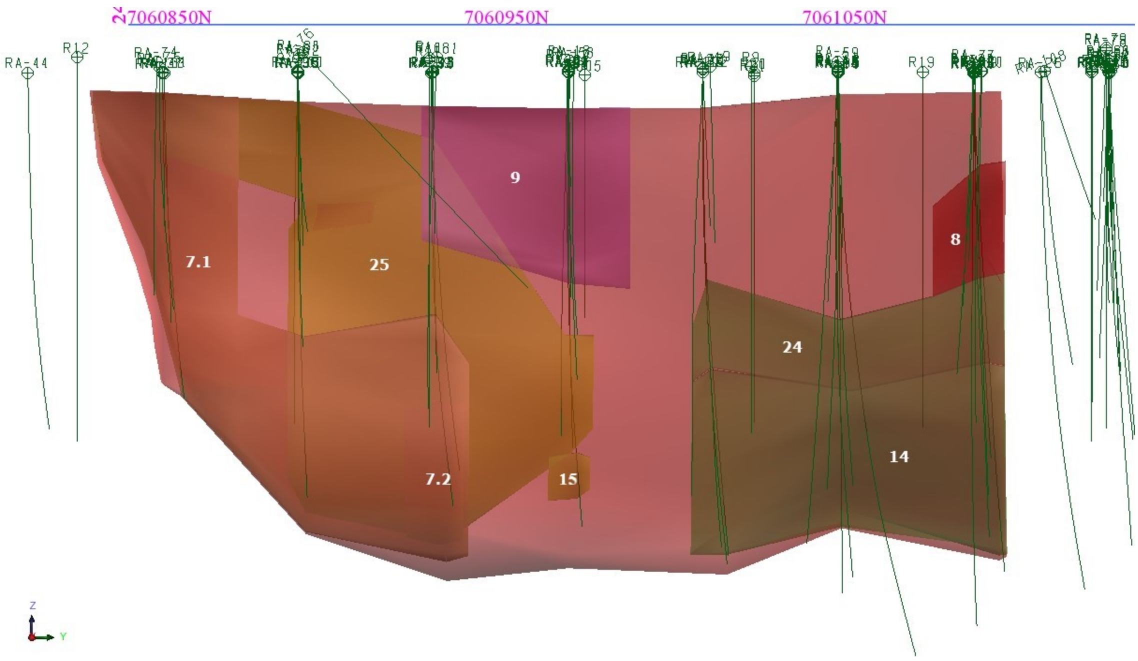


Figure 12. Longitudinal section of studied spodumene pegmatite vein at Rapasaari. Modelled barren pegmatites and black internal waste rocks of studied ore dike.

Volume of each solid is from Surpac enabling comparison to total volume of ore solid. Total volume of ore solid is 412,690 m^3 with Li_2O grade 1.04 %. Volumes of solids and percentages from the total volume are represented in Table 9.

Table 9. Lithologies, volumes and percentages of black waste rock and barren pegmatite solids from the total volume of the ore dike.

Solid ID	Lithology	Volume (m^3)	
		Solid	% from total
7.1	KL	9399	2.28 %
7.2	KL and PP	1130	0.27 %
8	KL	775	0.19 %
9	KL	2800	0.68 %
14	KL	11069	2.68 %
15	PP	58	0.01 %
Total		25231	6.11 %
24	MPG	3192	0.77 %
25	MPG	12395	3.00 %
Total		15587	3.77 %

5.3 Block modelling

Separate block model runs were done for black waste rock (Figure 13) and barren pegmatite (Figure 14). In the block model of black waste rock, each block is representing amount of waste rock dilution in each part of the ore dike. In the block model of white barren, each block is representing amount of barren pegmatite in the ore dike.

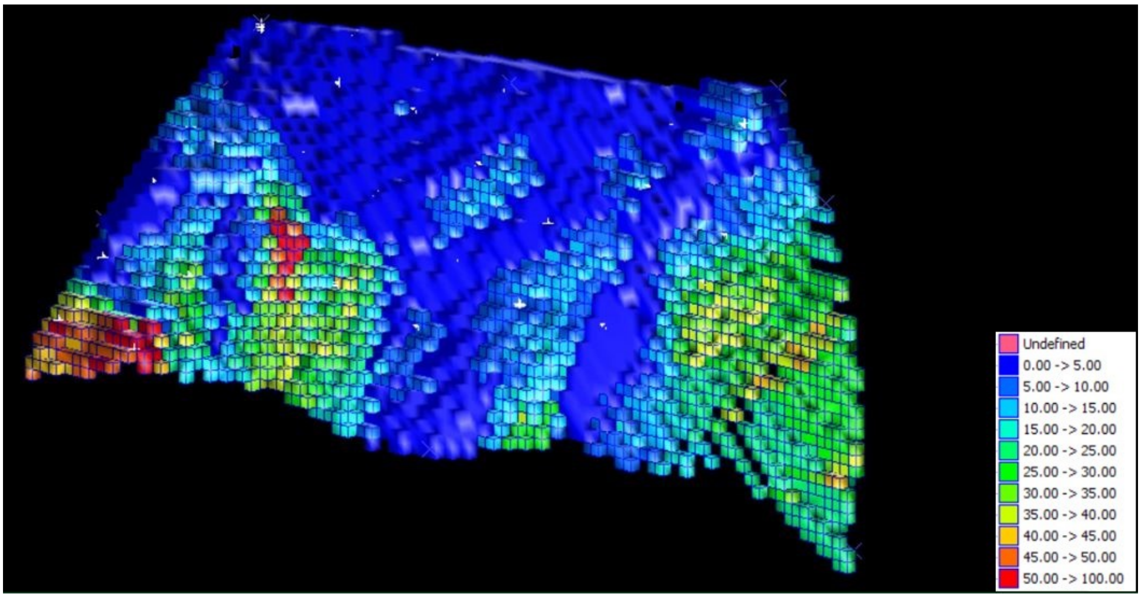


Figure 13. Block model for black waste rock. Colour scale is representing value of the sorting index (waste rock dilution) for black waste, blue is 0-5 %, red is over 50% (Loven 2018).

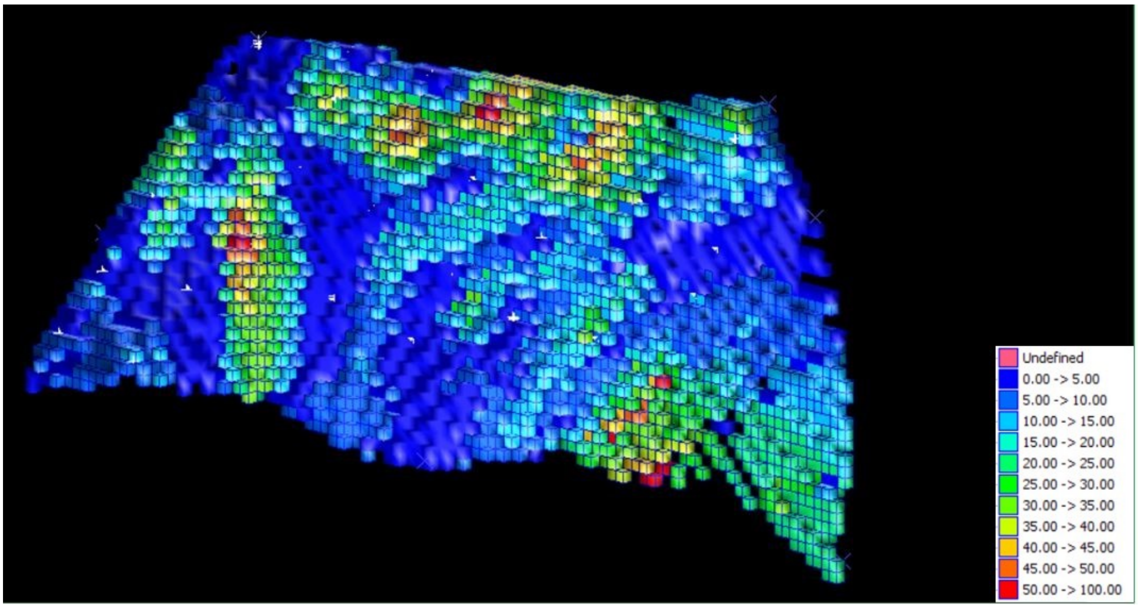


Figure 14. Block model of barren pegmatite. Colour scale is representing amount of barren pegmatite, blue is 0-5 % barren pegmatite, red is over 50 % (Loven 2018).

One-metre composites were used in estimations. Statistics of block models is in Table 10.

Table 10. Statistical values of block models (Loven 2018).

Variable	Black barren	Barren pegmatite
Number of samples	310	310
Min. value	0	0
Max. value	100	100
Mean	9.75	14.08
Variance	522.97	615.94
Standard deviation	22.87	24.82
Coefficent of variation	2.35	1.76

Volume of pegmatite below cut-off was 10,625 m^3 including 30.6 % barren pegmatite and 28.0 % black waste rock. Volume of ore-grade pegmatite was 511,750 m^3 with 13.6 % of barren pegmatite and 11.9 % of black waste rock. Total volume was 522,375 m^3, 1,420,860 tonnes, including 13.9 % barren pegmatite and 12.2 % black waste rock (Loven 2018).

5.4 Bench-scale sorting test

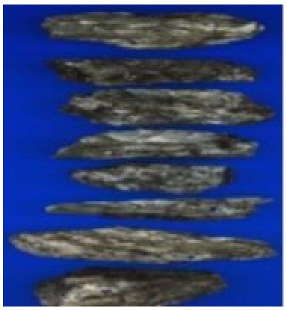
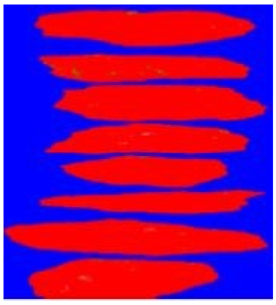
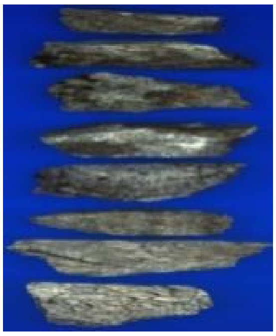
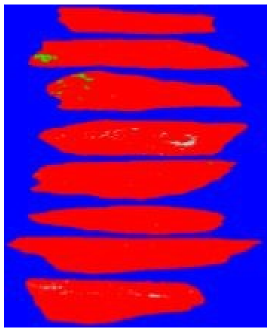
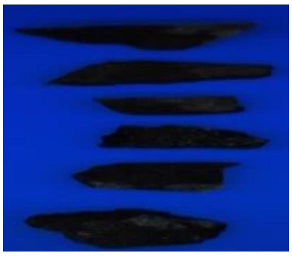
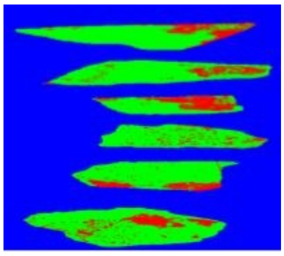
Bench-scale sorting test was conducted by engineers of TOMRA Sorting Solutions. Images and data of the following chapters are provided by TOMRA (2018) and used in this study with a permission of Keliber Oy. Drill core pieces were left out of the results, because physical state between samples was differing too much. In the final analysis, 60 of the most presentative samples were chosen from the sample groups for the sorting test.

5.4.1 COLOR

With the COLOR sensor, high-resolution pictures were taken of all samples and processed with image-processing software. Pixels of each picture were analysed and classified to different classes based on colour and brightness of the samples. The colour classes were defined as a percentage of the single rock area. The percentage was used to define the sorter threshold.

Spodumene pegmatite and barren pegmatite do not show any significant difference in their COLOR percentage. The average percentage of the Syväjärvi high- to low-grade spodumene pegmatite samples was 99.54 %. The average COLOR percentage for samples below cut-off and barren pegmatite was even higher, 99.76%. This can be seen also from images of Table 11, where any difference cannot be seen between spodumene bearing pegmatite and barren pegmatite. Spodumene pegmatite samples of the Länttä deposit were showing average percentage of 94.73. Black waste rocks had a significant difference in response. Their average percentage was 18.17 %. That enables the separation of pegmatite and black country rock with COLOR sensor.

Table 11. Raw and processed images of COLOR response analysis. Classification scheme and given colours: Ore: red and grey, waste: green, background: blue.

	Raw Image	Processed image
High-grade spodumene pegmatite		
Barren pegmatite		
Black waste		

COLOR sensor was able to classify all samples of product category as product. But on the other hand, barren pegmatite samples, which are internal waste, were not able to be separated by the sensor. The sensor separated 54 samples as product and 6 black waste rock samples as waste. The sensor ability to separate black rocks particles out of feed is 100 %, as it was previously proven.

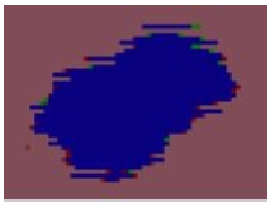
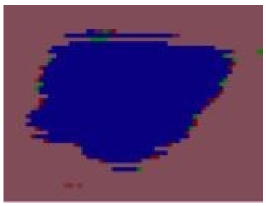
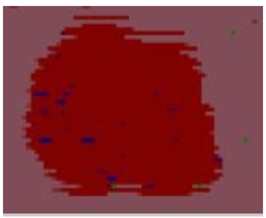
5.4.2 NIR

Starting point of the separation of spodumene and barren pegmatite with NIR analysis was challenging. The main minerals of the both pegmatite types are mainly the same. The only difference is the amount of spodumene, and spodumene does not have diagnostic response in NIR wavelengths. Nevertheless, in previous studies, spectral differences can be noticed around the water bands between spodumene, quartz and feldspar in the wavelengths of 1440-1900 nm (Figure 15).

Figure 15. NIR spectra (700-2500 nm) of feldspar, quartz and spodumene. Includes baseline corrected and offset spectra.

Samples were analysed after washing their surfaces. For each sample, a NIR index was calculated. The index was a measurement of the NIR spectra at the analysed zones of interest. These values were used for the determination of the sorting criteria. For the determination of the NIR index, differences in the shape of NIR spectrum were measured at several points within the sample. To get a relevant data set, multiple coefficients needed to be applied and plotted to virtual space. A classification model can be loaded in that virtual space. In Table 12, there are raw and processed images produced by NIR sensor. Different colour classes were defined as percentage from the single rock area. That percentage is used to determinate the sorting threshold.

Table 12. Raw and processed images of three samples by NIR. Classification scheme and given colours: Ore: blue, waste: red, background: pink.

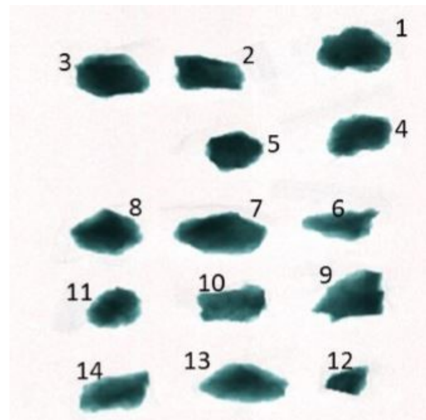
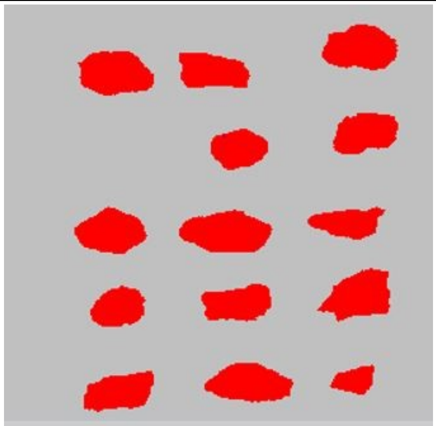
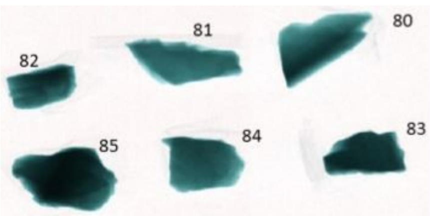
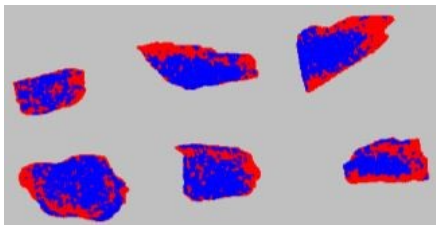
	NIR Raw Image	NIR Processed Image
High-grade spodumene pegmatite (Sample 2)		
Barren pegmatite (Sample 44)		
Black waste (Sample 80)		

Overall, it is possible to separate pegmatites and black waste rocks with the NIR sensor. Lack of differences in the spectra of silicate minerals causes separation of spodumene pegmatite and barren pegmatite impossible with the method.

5.4.3 XRT

The XRT method is based on differences in the X-ray intensity passing through the samples. The intensity changes were classified as either high density or low density. The density terms are used in a relative context because sensor is tailored for the material being tested. The density zones were defined as a percentage of the rock area. The percentage is used as the criterion of the separation. In Table 13, there are raw and processed images provided by the XRT sensor.

Table 13. Raw and processed images of the XRT sensor. Classification scheme and given colours; red: product, blue: waste, grey: background.

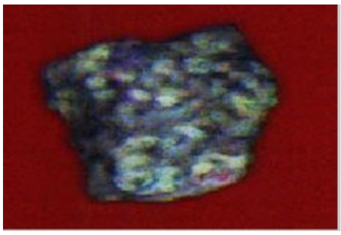
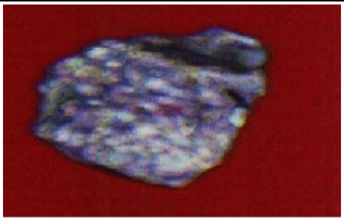
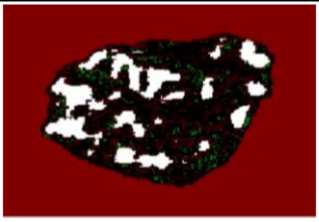
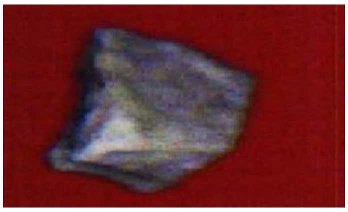
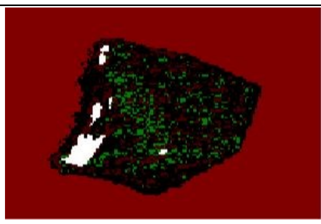
	Raw Image	Processed Image
High- and Medium-grade spodumene pegmatite		
Black waste rock		

Pegmatites, with or without spodumene, have quite a similar mineralogy and have no differences in the intensity of X-ray throughput. The XRT sensor can separate black waste rock from pegmatites as the COLOR and the NIR sensors are able to.

5.4.4 Multichannel LASER

Sorting is possible with the LASER system by grouping individual pixel responses into different colour categories. The LASER system uses wavelengths outside the visible spectrum, which is causing that the arbitrary colours of raw images are needed to be assigned. Table 14 is showing the raw and processed images obtained by the LASER system.

Table 14. Raw and processed images of the LASER sensor. Given colours: spodumene: white and green, waste: black, background red.

	Raw Image	Processed Image
High-grade spodumene pegmatite (Sample 1)		
High-grade spodumene pegmatite (Sample 2)		
Spodumene pegmatite below cut-off (Sample 25)		
Barren pegmatite (Sample 40)		
Black waste (Sample 85)		

As with all other sensor types, the separation of pegmatite samples and black waste rock is perfect, thus 100 %. The main difference between the LASER system and other tested systems, was that the LASER sensor was partly capable to separate spodumene pegmatite and barren pegmatite samples from each other, as it is shown in Table 14. Overall, the LASER sensor accepted 30 samples, which were classified as the product in the macroscopic classification, as products and rejected 4 product samples as waste getting 88 % as acceptance percent. Three of four rejected samples were from the Läntä deposit and one low-grade spodumene pegmatite sample from the Syväjärvi deposit. Two rejected samples of the Länttä deposit included reddish spodumene and one greenish. The sensor accepted 8 of 11 spodumene pegmatite samples considered to be below cut-off. One sample from nine barren pegmatite samples was accepted as the product and other samples were rejected, including all K-feldspar samples.

In Table 14, the sample number 40 is classified as barren pegmatite from the Syväjärvi deposit. In the macroscopic investigation there was no spodumene detected, only fine-grained muscovite. Although in the processed LASER image, there are white and green colours, which indicate spodumene. It is possible that fine-grained spodumene has not been detected in the sample grouping. Another possibility is that the system identified secondary muscovite as spodumene.

5.5 Hyperspectral imaging

Two mineral mapping techniques were used in the hyperspectral imaging. Both techniques provide quite similar results with few differences. The matching process is more sensitive for uncommon and rare minerals. Although, those minerals are not always well mapped, but over-estimated. Another technique is the data mining. The data mining method is providing more accurate mapping overall, but rare and uncommon minerals are getting lost. Combination of these two methods provides the most accurate results (TerraCore 2018b).

For the mineral mapping, LWIR camera with the data mining method was the method used to identify spodumene and visible in the mineral map (Figure 16). All main minerals were observed, but a small amount of albite was a surprise. There seemed to be much more K-feldspar and microcline than albite, which is not the case within albite-spodumene pegmatites. Some of the albite is certainly wrongly interpreted as microcline. These minerals have similar hyperspectral signatures. There are also muscovite and chlorite found, but alteration in grain margins of spodumene is not visible.

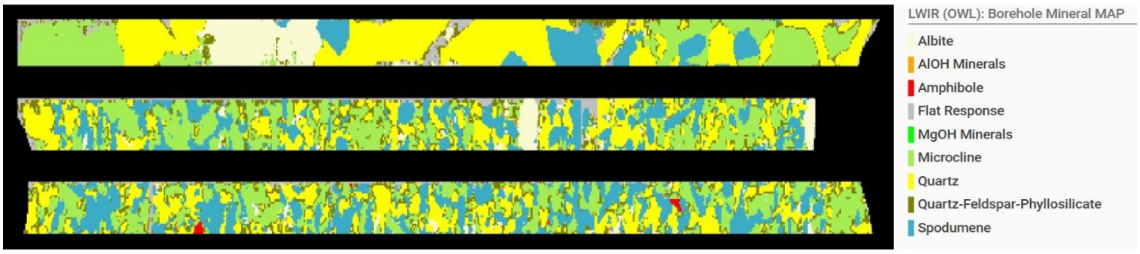


Figure 16. LWIR Borehole Mineral Map from 115.40 to 118.20 metres in RA-88 drill core.

Overall, a wide variety of minerals were mapped including expected main minerals. Also, several rarer minerals were present. For example, ammonium-bearing K-feldspar, buddingtonite, was found, in spodumene pegmatite of RA-86 drill core by both processing techniques. Buddingtonite is not previously recorded within pegmatites, but it is a common associate within precious metal deposits (Terracore 2018b). Analcime and illite occur within pegmatites. Ammonium illite is present in the drill core RA-86. Source of ammonium is in most cases organic-rich lithologies.

6 DISCUSSION

6.1 Significance of the developed index

Sorting index is developed to make the estimation of waste rock dilution and waste rock modelling easier. With the specified drill core logging procedure, that was developed with more precise logging near to spodumene pegmatite intercepts and percentages of spodumene pegmatite, barren pegmatite and black waste rock is giving more accurate knowledge from the ore body. The index considered also small waste rock inclusions, which may not be separated otherwise in drill core logging. The collected data can be used in waste rock modelling. In the modelling, the known amount of internal waste rocks is providing useful information for mine planners. The index is an additional parameter, so there is possibility to use it in block modelling and resource estimation. When the index is used in block modelling, waste rock dilution, need for sorting and its outcome can be estimated straight from the model. Data can be used in mining, mine planning and loading at the mine site. The index can be used also in calculations of blocks' values (see chapter 6.4).

If barren pegmatites cannot be separated from the feed of concentration plant, knowing the amount of internal barren pegmatite is also an important factor in the process optimization. The developed index is also providing amount of barren pegmatite which can be used for more accurate grade estimation of the feed.

Working with historical drill core data, there may be situations when sampling is not done properly, or it is not corresponding for today's needs by other ways. For example, if sampling is done by one-metre intervals without a consideration of rock types, there may be assay intervals including both ore and waste rock with varying ratios. With relogging procedure that includes the sorting index, it is possible to get the ore and waste rock separated without re-sampling. In that case, there also needs to be assays including only ore or waste rock. Thereafter the average grade of waste rock is known, and the ore grade can be calculated from mixed assays.

6.2 Comparison to previous studies

Bench-scale sorting test was focused to separate barren pegmatite pieces from spodumene pegmatite pieces. As the perfect separation of black waste rock in the previous pilot-scale sorting test, it was proven again with all sensor types in this study. The new test provided options to separate spodumene bearing pegmatite and barren pegmatite with the LASER sensor. Nevertheless, more research should be done with larger sample amount including pegmatites with different grades and grain sizes, to get the separation potentiality proved with higher certainty.

According to Kurtti (2018), the alteration degree of spodumene is 15-30 % in spodumene pegmatite dikes within the Rapasaari deposit. The quantify of altered spodumene depends on size and depth of a pegmatite dike. The mentioned percentages are only assumptions, and they are based on calculations from dispersion halo of lithium in country rocks. Origin of lithium in country rocks is assumed to be from spodumene-bearing pegmatite dikes. Comparing the result with the sorting index calculations similarities are found. The amount of barren pegmatite (14 %) from the relogged data, seems to be correlating with geochemical data. However, all muscovite bearing pegmatite in the dikes is not altered, because there are also primary muscovite pegmatites. Therefore, too far-reaching conclusions cannot be done.

6.3 Hyperspectral separation and sensor-based sorting

It is proven that pegmatite can be separated from black waste rock by optical and XRT sensors. Spodumene does not have characteristic spectral response in NIR wavelengths and low colour contrasts to other minerals are making separation of spodumene pegmatite and barren pegmatite impossible with NIR and colour sensors. Only the multichannel LASER sensor in the SBS test could partly sort pieces of spodumene and barren pegmatites pieces.

Samples of the sorting test were grouped by estimating the amount of spodumene. In Table 3, is shown that samples considered to be below cut-off, have grade above cut-off. Barren pegmatite composite sample also has a quite high concentration of lithium. A reason for that may be in the nugget effect. Spodumene occurs mostly as large crystals: One or two large crystals can raise grade from below cut-off to above cut-off. Although, the samples were picked from ore piles containing mostly high-grade ore. It caused that finding barren pegmatite and low-grade rocks was difficult.

In hyperspectral imaging, spodumene had good response in LWIR wavelengths. Unfortunately, the LWIR cameras cannot be utilized in the sensor-based sorting because the imaged material need to be pre-heated. In addition, a lot of time is needed for data processing and it does not identify minerals rapidly. Alteration of spodumene crystals was possible to see in some cases, but pixel size of HS cameras is too large for the smallest features in the margins of spodumene crystals. That is arousing a question, does the HS system detect and identify very fine-grained minerals, and in that case, spodumene.

In mineral maps of hyperspectral imaging test, amount of albite was quite low, approximately less than 10 %. Based on MLA studies of the pegmatites of Kaustinen region, albite content should be over 30 % within all deposits (Table 5). Amount of K-feldspar (microcline) seemed to be relatively high in HS study compared to MLA results. Only explanation is that, most of the K-feldspar detected in HS study is albite. Albite and K-feldspar have quite similar spectral spikes and therefore they may overlap.

6.4 Economic consideration

As previously mentioned, SBS may decrease operational costs in several process stages, including grinding, flotation, dewatering, pumping and transportation. In a case, where ore needs to be transported to a concentration plant, savings can be significant when waste rock can be separated at a mine-site.

In the case above, a solution is semi-mobile installation of SBS plant. Then the sorter can be transported to the mine-site and the fines as well as separated waste rock can be put directly to waste dump or tailings facility. Transportation of sorter makes possible, for example, seasonal sorting, if there is no need for continuous sorting. According to Robben (2013), an exemplary investment of stationary installation is 46 % lower than a semi-mobile installation. Operating costs are depending on particle size of a feed. Energy, labour and maintenance cover major part of the total operating costs. Operating costs of stationary installation are ca. 42 % lower per tonne of feed and 45 % lower per tonne of product than a semi-mobile installation (Robben 2013).

Focusing on mining and processing the ore, sorting may increase the value of a block by separating black country rock out of the feed. By sorting, the head grade of the feed can be increased. At the same time, the waste rock dilution decreases, which have a positive effect in the flotation circuit of spodumene (Salvador 2017). When dilution is minimized from the plant feed, higher recovery of spodumene is achieved. In Figure 17, there is an example for increasing of the value of a block by SBS. There are 4 blocks with the same 0.45 % Li_2O-grade, but with different relationships of the rock types. The block number 1 consists only spodumene pegmatite below cut-off grade making it unprofitable to exploit. With the separation potential of the multichannel LASER system, it could be possible to separate ~85 % of barren pegmatite pieces out of the feed. That is increasing the lithium grade of the accept and thus the value of the block number 2, making it profitable to be exploited. With other sensor systems, value of the block cannot be increased. Within the block number 3, there is spodumene pegmatite and black waste rock with 1:1 ratio. The black waste rock can be separated out of the feed by all sensor systems. That increases the grade of the block significantly making it profitable to be exploited. The block number 4 has half of spodumene pegmatite and quarters of barren pegmatite and black waste rock. Each sorter systems can separate black waste rock out of the feed but may leave the barren pegmatite. The separation of black waste rock increases the value of the block, which can make it profitable to be exploited. With the separation of barren pegmatite also, the value of the block 4 will increase significantly making it exploitable for sure. This example shows the potential of developed method to increase the mineral resources and ore reserves. For the accurate calculations required one needs to include the processing costs of different alternatives as well as the mass proportion of the fine material bypassing the sorter.

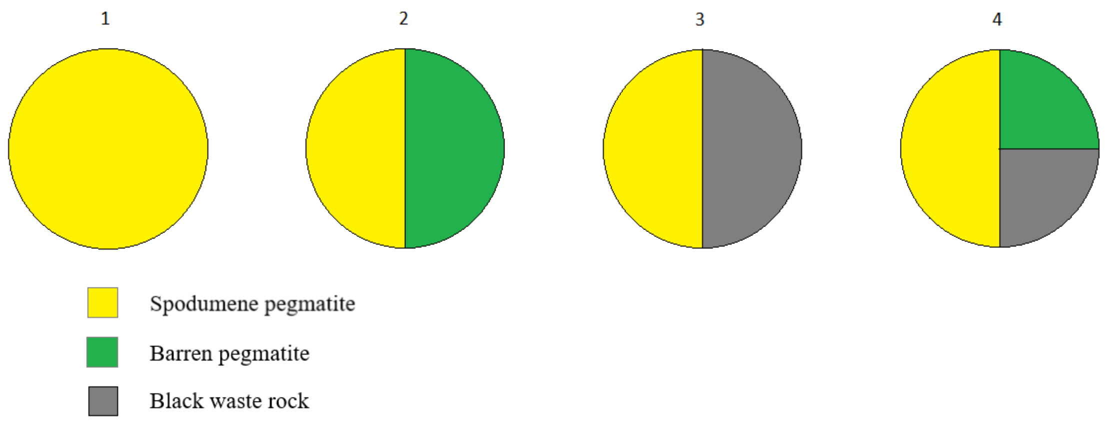


Figure 17. Four blocks with same Li_2O-grade (0.45 %), but with different relationships of rock types.

7 SUMMARY AND CONCLUSIONS

7.1 Summary

The aim of the study was development of an index, that can be used in the estimation of waste rock dilution. The index was defined during drill core relogging. Block model with attributes for black waste rock and barren pegmatite was created based on relogged drill core data.

Separation of spodumene pegmatite and barren pegmatite was studied in a bench-scale sorting test. Also, abilities of sensor systems were verified in separation of pegmatite and black waste rock. Some notes from the sorting test:

- COLOR, NIR, XRT and Multichannel LASER sensor systems of TOMRA Sorting Mining were used
- All sensor systems separated pegmatite and black country rock with 100 % probability
- Multichannel LASER was only sensor system able to separate spodumene bearing pegmatite and barren pegmatite with a probability of 88 %

In a hyperspectral imaging study, minerals were found, which were not previously identified in pegmatites of Kaustinen region, for example buddingtonite. The system did not always identify albite and K-feldspar from each other due the quite similar spectral spikes.

7.2 Conclusions

The main objective of the study was the development of an index, which can be used in an estimation of waste rock dilution. This objective was achieved. The developed index is easy to define during drill core logging and does not increase logging time significantly. It can be done from the high-quality drill core photos also. It can be used in block modelling as an attribute. In block modelling, the index shows the waste rock dilution in every part of a deposit. The index is not only suitable for spodumene pegmatite ores, but can be used with all deposits, where ore and waste rock can be defined during drill core logging. The main application of the index is with vein-type deposits or with deposits, where several ore bodies exist in a small area. When mining that kind of deposits, amount of waste rock is high and more accurate data about waste rock dilution will give advance in mine planning. For example, in a pre-stripping stage of a mine, it is possible to get narrow spodumene pegmatite veins to feed by SBS, when veins locations are known. Loads including material from the veins need to be piled in different locations at a site as waste rock loads. Those piles can be sorted later.

Another aim of the study was to find methods to separate spodumene and barren pegmatite with SBS. The LASER system gave promising results for the separation of spodumene and barren pegmatite. As it is seen in Table 14, it is possible to set a threshold value for white colour and get some of the barren pegmatite out of the feed. The result gave a good start point for the future's sorting tests. If the LASER system works in pilot-scale tests, it will make significant savings in the process costs. The separation of black waste rock and pegmatites was proved to be 100 % with all sensor systems. Contacts of spodumene pegmatite dikes were often free from spodumene (see Figure 9). If it is known, that there would be a high-grade spodumene pegmatite close to a contact, a sorting threshold can be set to accept small amount of waste rock, when that material is fed to a sorter. That enables use of different sorting thresholds for waste rock without major recovery losses of spodumene.

7.3 Recommendations for further activities

Several recommendations are suggested, that can be considered in the future based on this thesis project. At first, it is possible to do the sorting index for all drill core log data. If there is need for more accurate data from historical drill cores, the sorting index can be created from drill core photos. Old drill core logs provide also useful information, that will help with relogging. Current logging procedure is recommended to be changed to the logging procedure including the sorting index as soon as possible. If it is found, that the separation of spodumene pegmatite and barren pegmatite is not beneficial or there is no need to separate spodumene-bearing and barren pegmatite, it is possible to simplify the index. Then only the amounts of white rocks and black rocks need to be separated. On the other words, index values of spodumene pegmatite and barren pegmatite can be merged in drill core logging.

There is a need for new SBS test program. Especially promising result was found from separation of spodumene pegmatite and barren pegmatite by the LASER system, but much more investigations are needed to prove that it works in all circumstances. A pilot-scale SBS tests are the way to investigate this matter. In the pilot-scale SBS test, it is recommended to use the multichannel LASER system. It enables testing of different threshold-values for the separation of spodumene and barren pegmatite. Separation of pegmatites and black waste rock will work with all particle sizes and with all spodumene grain sizes. In separation of pegmatites, size of sorted material could be crucial to consider at future’s sorting tests. Separation of spodumene-bearing particles may be easier when particle size is smaller and spodumene liberation stage higher. Smaller particle size increases crushing costs and the amount of fines with decreasing feed capacity of sorting process. All above mentioned things have influence to profitability of sorting process and need to be studied. It is also important to study, how does the grain size of spodumene affect to the separation of spodumene and barren pegmatite.

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APPENDIX 1: A relog of RA-37 drill core

Keliber Oy

Core logging sheet

Hole: RA-37 **Direction / dip (plan):** / **Logged / date:** 19.11.2017/HJÄ

CL = core loss S-T = structure / texture Spo width (mm) CA = core angle **Sign:**

From (m)	To (m)	m	CL cm	RQD cm	Rock code	S-T code	Weath. code	Spo angle	Spo size	Spo %	SPG %	White %	Black %	C type	CA Deg.	Assay id 2014 .....
11,00	12,90	1,90		190	SPG		1	-	4	8	100	0	0			41 009
12,90	14,90	2,00		197	SPG		1	-	3	15	100	0	0	3		41 011
14,90	15,60	0,70		17	KL		1				0	0	100			
15,60	17,15	1,55		155	SPG		1	-	4	15	100	0	0	3		41 012
17,15	18,15	1,00		91	KL		1				0	0	100			
18,15	19,15	1,00		92	KL		1				0	0	100			
19,15	20,15	1,00		88	KL		1				0	3	97			
20,15	23,55	3,40		275	KL		1				0	1	99			
23,55	24,55	1,00		80	KL		1				0	7	97			
24,55	25,55	1,00		55	KL		1				0	0	100			
25,55	26,50	0,95		10	SPG		1	-	6	7	50	50	0	2		41 013
26,50	27,75	1,25		90	SPG		1	-	4	15	100	0	0			41 014
27,75	28,50	0,75		75	MPG		1				0	100	0	1		41 015
28,50	29,15	0,65		25	KL		1				0	3	97			
29,15	30,25	1,10		85	SPG		1	-	15	20	100	0	0	1		41 016
30,25	31,85	1,60		160	SPG		1	-	3	12	100	0	0			41 017
31,85	33,20	1,35		135	SPG		1	-	2	10	100	0	0			41 018
33,20	34,70	1,50		150	SPG		1	-	4	13	100	0	0			41 019
34,70	35,95	1,25		125	SPG		1	-	2	5	60	40	0			41 021
35,95	37,20	1,25		121	SPG		1	-	2	5	60	40	0			41 022
37,20	38,65	1,45		145	SPG		1	-	10	15	100	0	0			41 023
38,65	40,20	1,55		150	SPG		1	-	8	20	100	0	0	3		41 024
40,20	40,70	0,50		50	PP		1				0	20	80			
40,70	42,80	2,10		200	SPG		1	-	4	7	97	0	3	1		41 025
42,80	43,15	0,35		0	PP		1				0	0	100			
43,15	44,70	1,55		110	SPG		1	-	3	12	100	0	0	1		41 026
44,70	45,20	0,50		42	PP		1				0	0	100			
45,20	45,50	0,30		30	MPG		1				0	100	0	1		41 027
45,50	46,50	1,00		100	PP		1				0	0	100			
46,50	48,05	1,55		148	PP		1				0	0	100			
48,05	48,90	0,85		85	KA		1				0	70	30			
48,90	49,25	0,35		35	PP		1				0	0	100			
49,25	50,10	0,85		85	SPG		1	-	6	10	100	0	0	1		41 028
50,10	50,45	0,35		35	PP		1				0	20	80			
50,45	51,50	1,05		105	KL		1				0	0	100			
51,50	52,95	1,45		128	SPG		1	-	4	18	100	0	0	3		41 029
52,95	53,75	0,80		80	SPG		1	-	3	5	20	80	0	1		41 031
53,75	54,75	1,00		100	KL		1				0	2	98			
54,75	55,75	1,00		100	KL		1				0	3	97			
55,75	56,75	1,00		100	KL		1				0	0	100			
56,75	65,50	8,75		720	KL		1									
65,50	67,70	2,20		110	KL		1									
67,70		-67,70			EOH											

APPENDIX 2: The sorting index calculation from relog data of RA-37 drill core.

Hole id	from	to	length	lithology	Li2O tot	Li2O interpr.	White ore%	White barren%	Black waste%	ore length	white length	black length	C-type
RA-37	11	12,9	1,9	SPG	1,240128	1,240128	100	0	0	1,90	0,00	0,00	
RA-37	12,9	14,9	2	SPG	1,504947	1,504947	100	0	0	2,00	0,00	0,00	3
RA-37	14,9	15,6	0,7	KL	-1	0,2	0	0	100	0,00	0,00	0,70	
RA-37	15,6	17,15	1,55	SPG	1,498488	1,498488	100	0	0	1,55	0,00	0,00	3
RA-37	17,15	18,15	1	KL	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-37	18,15	19,15	1	KL	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-37	19,15	20,15	1	KL	-1	0,2	0	3	97	0,00	0,03	0,97	
RA-37	20,15	23,55	3,4	KL	-1	0,2	0	1	99	0,00	0,03	3,37	
RA-37	23,55	24,55	1	KL	-1	0,2	0	7	97	0,00	0,07	0,97	
RA-37	24,55	25,55	1	KL	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-37	25,55	26,5	0,95	SPG	0,305726	0,305726	50	50	0	0,48	0,48	0,00	2
RA-37	26,5	27,75	1,25	SPG	1,619056	1,619056	100	0	0	1,25	0,00	0,00	
RA-37	27,75	28,5	0,75	MPG	0,630829	0,630829	0	100	0	0,00	0,75	0,00	1
RA-37	28,5	29,15	0,65	KL	-1	0,2	0	3	97	0,00	0,02	0,63	
RA-37	29,15	30,25	1,1	SPG	3,46633	3,46633	100	0	0	1,10	0,00	0,00	1
RA-37	30,25	31,85	1,6	SPG	1,543701	1,543701	100	0	0	1,60	0,00	0,00	
RA-37	31,85	33,2	1,35	SPG	1,942006	1,942006	100	0	0	1,35	0,00	0,00	
RA-37	33,2	34,7	1,5	SPG	2,153	2,153	100	0	0	1,50	0,00	0,00	
RA-37	34,7	35,95	1,25	SPG	0,779386	0,779386	60	40	0	0,75	0,50	0,00	
RA-37	35,95	37,2	1,25	SPG	1,575996	1,575996	60	40	0	0,75	0,50	0,00	
RA-37	37,2	38,65	1,45	SPG	1,586761	1,586761	100	0	0	1,45	0,00	0,00	
RA-37	38,65	40,2	1,55	SPG	1,132478	1,132478	100	0	0	1,55	0,00	0,00	3
RA-37	40,2	40,7	0,5	PP	-1	0,2	0	20	80	0,00	0,10	0,40	
RA-37	40,7	42,8	2,1	SPG	0,691113	0,691113	97	0	3	2,04	0,00	0,06	1
RA-37	42,8	43,15	0,35	PP	-1	0,2	0	0	100	0,00	0,00	0,35	
RA-37	43,15	44,7	1,55	SPG	1,315483	1,315483	100	0	0	1,55	0,00	0,00	1
RA-37	44,7	45,2	0,5	PP	-1	0,2	0	0	100	0,00	0,00	0,50	
RA-37	45,2	45,5	0,3	MPG	0,022607	0,0226065	0	100	0	0,00	0,30	0,00	1
RA-37	45,5	46,5	1	PP	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-37	46,5	48,05	1,55	PP	-1	0,2	0	0	100	0,00	0,00	1,55	
RA-37	48,05	48,9	0,85	KA	0,002	0,002	0	70	30	0,00	0,60	0,26	
RA-37	48,9	49,25	0,35	PP	-1	0,2	0	0	100	0,00	0,00	0,35	
RA-37	49,25	50,1	0,85	SPG	1,227	1,227	100	0	0	0,85	0,00	0,00	1
RA-37	50,1	50,45	0,35	PP	-1	0,2	0	20	80	0,00	0,07	0,28	
RA-37	50,45	51,5	1,05	KL	-1	0,2	0	0	100	0,00	0,00	1,05	
RA-37	51,5	52,95	1,45	SPG	1,70087	1,70087	100	0	0	1,45	0,00	0,00	3
RA-37	52,95	53,75	0,8	SPG	0,811681	0,811681	20	80	0	0,16	0,64	0,00	1
RA-37	53,75	54,75	1	KL	-1	0,2	0	2	98	0,00	0,02	0,98	
RA-37	54,75	55,75	1	KL	-1	0,2	0	3	97	0,00	0,03	0,97	
RA-37	55,75	56,75	1	KL	-1	0,2	0	0	100	0,00	0,00	1,00	
RA-37	56,75	65,5	8,75	KL						23,27	4,13	18,38	
RA-37	65,5	67,7	2,2	KL						50,82 %	9,03 %	40,15 %	